Outcomes of anterior cruciate ligament reconstruction from 2 to 20 years post-surgery: a mixed-method approach

Mandeep Kaur

A thesis submitted for the degree of

Doctor of Philosophy (PhD)

At the University of Otago, Dunedin,

New Zealand

April, 2018

Abstract

Background: Rupture of Anterior Cruciate Ligament (ACL) is one of the common injuries during sports world-wide. Repair of the ruptured ligament with reconstruction is considered as a primary treatment option, especially for those persons who want to return to sport. Persons with such injury are considered to be at 10% higher risk of osteoarthritis. Participants present with reduced muscle strength, physical performance and altered gait pattern following surgery. As osteoarthritis is a multifactorial disease, exploring the muscle strength, physical performance, knee laxity and biomechanics along with the participants' perspectives related to their knee health would provide insights regarding the recovery in participants with anterior cruciate ligament reconstruction (ACLR).

Thesis aims: The overall aim of this thesis was to explore medium (2-10 years) and long-term (10- 20 years) outcomes of ACLR in New Zealand.

Specific aims were, firstly, to determine medium (2-10 years) and long-term (10-20 years) outcomes of current management of ACLR in terms of muscle strength, physical performance, knee laxity and biomechanical outcomes, with an emphasis on risk factors associated with post-traumatic osteoarthritis. The second aim was to explore the participants' experiences of the outcomes of their surgery more than 2 years in relation to physical activity, sports, occupation and quality of life. Thirdly, the relationship between knee moments and participant-related factors such as muscle strength, time since surgery and sex of the participants was explored.

Methods: A series of five related studies were conducted to explore the outcomes of ACLR more than 2 years following surgery. A systematic review and meta-analysis (Study 1)

reviewed the literature focusing on the knee angles and moments in participants with ACLR compared to the contralateral limb and uninjured Control groups during walking, stair navigation and jogging activities (Study 1). Reviewing the literature related to the muscle strength and physical performance provided support for a cross-sectional study to explore the patient-reported outcomes [comprising Tegner physical activity scale, Knee Injury Osteoarthritis Outcome Scale (KOOS), Confidence during sports Scale, and Short form-12 (SF-12) Health Survey], thigh muscle strength, physical performance and knee laxity in participants with ACLR. Results of ACLR group were compared to the Control group (Study 2). A qualitative study was conducted to gain deeper insight into the participants' perspectives related to their knee health, 2-10 years following surgery (Study 3). A cohort of ten participants took part in the face to face semi-structured interviews. The systematic review and meta-analysis (Study 1) provided the methodological insights for the main cross-sectional study (Study 4) regarding the study design, task for analysis and the variables. To explore the knee angles and moments on injured side in participants with ACLR, a cross-sectional study analysed the peak angles and moments in participants with ACLR during stair navigation 2-10 years of following surgery and results were compared to the contralateral limb and the uninjured Control group (Study 4). Results of the systematic review also informed the variables for the next biomechanical study exploring the association of peak flexion and adduction moments with the muscle strength, time since injury and sex of the participants with ACLR. This study involved 35 participants with ACLR from 2 to 20 years following surgery, and biomechanical variables and muscle strength were measured (Study 5).

Results: Results of the systematic review and meta-analysis (Study 1) indicated that joint kinematics of ACL reconstructed knees were similar to Control groups during walking and stair navigation within a few months after surgery. The meta-analysis indicated lower pooled external peak flexion moments for people with ACLR compared to controls during walking and stair ascent. Furthermore, inspection of the forest plots indicated potentially increased peak adduction moments over time following ACLR. Results of Study 2 indicated that participants with ACLR had lower quadriceps eccentric quadriceps strength (p=0.004), physical performance (p=0.019), and higher knee laxity (p=0.027) on the injured side compared to the contralateral knee. Participants with ACLR had higher knee-related pain and symptoms (p<0.001), and poor knee function in sports and quality of life domains (p<0.001) on the KOOS scores compared to the uninjured Control group (Study 2). Participants with ACLR indicated lower scores in Confidence during sports scale, indicating the presence of fear of injury. There was no differences in the level of physical activities among both groups (p=0.009). Results of the qualitative study (Study 3) indicated presence of fear of injury, behavioural manifestations of the fear of injury, and low confidence during sports in most of the ten participants. Results of the cross-sectional study (Study 4) indicated lower peak knee flexion angle in participants with ACLR compared to the Control group on the injured side (p=0.022). Participants with ACLR had lower peak flexion moment (p=0.024) and higher extension moment (p=0.027) on the injured side compared to the contralateral knee during stair ascent. There were no significant differences in the adduction moment on the injured side compared to the contralateral knee in participants with ACLR knee compared to the Control group during stair navigation. Further results from the next cross-sectional study (Study 5) indicated significant associations between the knee flexion moment and concentric quadriceps muscle strength ($p < 0.001$) and sex of the participant ($p = 0.026$) during stair ascent, while no association was present with the time since surgery. There were no significant associations between the muscle strength, time since surgery and the sex of the participants with knee adduction moments during ascent and descent.

Conclusion: Physical impairments persist mid- to long-term in participants with ACLR. Quadriceps eccentric strength, in particular, does not recover fully. Peak knee flexion moments are reduced on the injured side compared to the contralateral side in participants with ACLR. Furthermore, knee flexion moments are associated with the concentric quadriceps strength and sex of the participants during stair ascent. Women seem to have higher knee flexion moment. Therefore, strengthening the thigh muscle groups may help in restoring and optimising moment symmetry. Persisting fear of injury and low confidence levels in sports was described by a sub-group of the participants. Physical and psychological impairments persist in the mid- to long-term following injury and surgery, therefore, optimum measures targeting those impairments depending on the individual requirement are required to improve the surgical and rehabilitative outcomes and decrease the patient burden.

Acknowledgements

I owe my deepest gratitude to my primary supervisor Dr. Gisela Sole for taking me on board as part of her research team. Without her enthusiasm, encouragement, and support this study would hardly have been completed. Her vision, precision and motivation have deeply inspired me. She has taught me the methodology to carry out the research and to present it as clearly as possible. It was a great privilege to work under her guidance. I also express my warmest gratitude to my co-supervisor Dr. Daniel Cury Ribeiro, for his invaluably constructive and friendly advice throughout this thesis. His guidance into the data collection and analysis has been essential during this work. I am deeply grateful to my advisor Associate Professor Kate Webster, La Trobe University (Australia) and Professor Jean Claude-Theis, Orthopaedic Surgeon, for providing me feedback from time to time.

I would like to acknowledge the Centre for Health Activity and Rehabilitation Research (CHARR), School of Physiotherapy, for valuable contributions in the implementation of this study. I would like to thank all the administrative and technical staff in the School for providing the required support. I want to thank Dr. Marina Moss for helping me in the recruitment process and other timely help. Special thanks to Bruce Knox for helping me to learn the technical details related to biomechanics data. I want to thank Mr Andrew Gray for enlightening me regarding statistical issues. Special thanks to Peter Lamb, lecturer at School of Physical Education, Sport and Exercise Sciences, for helping me with his technical expertise. Lastly, I thank my participants without whom this thesis would not be possible at all.

I would also like to thank all of my friends and fellow PhD colleagues- Poonam Mehta, Aleksandra Mącznik, Arun Prasad Balasundaram, and Codi Ramsey who supported me throughout this journey.

Finally, I would like to thank my family for supporting me throughout my life and during my PhD. I would like express deepest appreciation to my husband, Sanchit Sandhu, who was my support whenever things were most challenging. This expedition could not have been completed without him!

Refereed publications

Kaur, M, Ribeiro D.C, Theis, J.C., Webster, E.K, Sole. G. Movement patterns of the knee during gait following ACL reconstruction: a systematic review and meta-analysis. *Sports Medicine* 1-27, 2016. DOI 10.1007/s40279-016-0510-4.

Refereed published abstracts

Kaur, M, Ribeiro D.C, Theis, J.C., Webster, E.K, Sole. G. Movement patterns of the knee during gait following ACL reconstruction: a systematic review and meta-analysis. *Physiotherapy New Zealand Conference*, page 77, Auckland, New Zealand, 2016.

Kaur, M, Ribeiro D.C, Theis, J.C., Webster, E.K, Sole. G. Differences in sagittal plane kinematics and kinetics during stair negotiation in participants with Anterior Cruciate Ligament reconstruction compared to Control group. *International Society of Biomechanics conference*, page 159, Brisbane, Australia, 2017.

Kaur, M, Ribeiro D.C, Theis, J.C., Webster, E.K, Sole. G. Participants' perspectives of anterior cruciate ligament reconstruction surgery. *Otago Research symposium*, page 42, University of Otago, New Zealand, 2017.

Refereed conference presentations

Kaur, M, Ribeiro D.C, Theis, J.C., Webster, E.K, Sole. G. Movement patterns of the knee during gait following ACL reconstruction: a systematic review and meta-analysis, at '*Arthritis theme meeting'*, held at Dunedin, University of Otago, 2015. (Platform).

Kaur, M, Ribeiro D.C, Theis, J.C., Webster, E.K, Sole. G. Movement patterns of the knee during gait following ACL reconstruction: a systematic review and meta-analysis, at *Physiotherapy New Zealand*, 2016 Conference, Auckland, New Zealand. (Platform).

Kaur, M, Ribeiro D.C, Theis, J.C., Webster, E.K, Sole. G. Differences in sagittal plane kinematics and kinetics during stair negotiation in participants with Anterior Cruciate Ligament reconstruction compared to control group, *International Society of Biomechanics conference*, Brisbane, Australia, 2017. (Platform).

Kaur, M, Ribeiro D.C, Theis, J.C., Webster, E.K, Sole. G. Participants' perspectives of anterior cruciate ligament reconstruction surgery, *Otago Research symposium*, University of Otago, 2017. (Platform).

Table of contents

Contents

Abstract i

Acknowledgements v

Refereed publications vii

Table of contents ix

List of tables xv

List of figures xvii

List of abbreviations xix

1 Introduction 1

1.1 Background 1

1.2 Need of mixed-method thesis 3

1.3 Research question 5

1.3.1 Thesis aims 5

1.3.2 Study objectives 6

1.4 Research pathway 7

1.5 Significance of the research 9

2 Literature review 11

2.1 Prelude to Chapter 2 11

2.2 Background 12

2.3 Anterior cruciate ligament injury and management 12

2.4 Consequences of Anterior cruciate ligament reconstruction 14

2.4.1 Re-injury of the ligament 14

2.4.2 Post-traumatic osteoarthritis 16

2.5 Recovery process following the anterior cruciate ligament reconstruction 18

2.5.1 Muscle strength-related outcomes 18

2.5.2 Physical performance in participants with ACLR 21

2.5.3 Knee laxity following anterior cruciate ligament reconstruction 23

2.6 Patient-perspectives following anterior cruciate ligament reconstruction 25

2.6.1 Person-centred treatment approach 26

2.6.2 Quality of life following ACL reconstruction 27

2.6.3 Patient-reported outcomes 32

2.7 Summary 35

3 Movement patterns following ACL reconstruction: a systematic review and meta-analysis 37

3.1 Prelude to Chapter 3 ... 37
3.2 Background ... 38
3.3 Methods ... 40
3.3.1 Search strategy and study selection ... 40
3.3.2 Data extraction and meta-analysis ... 42
3.3.3 Level of evidence ... 43
3.4 Results ... 44
3.4.1 Search results ... 44
3.4.2 Risk of bias ... 45
3.4.3 Overview of included studies ... 49
3.4.4 Meta-analyses ... 68
3.4.5 Joint angles ... 71
3.4.6 Joint moments ... 74
3.4.7 Time course of recovery ... 78
3.5 Discussion ... 79
3.5.1 Peak joint angles ... 79
3.5.2 Joint moments ... 80
3.5.3 Clinical implications ... 83
3.5.4 Methodological considerations and directions for future research ... 84
3.6 Conclusion ... 85
3.7 Summary ... 86
4 Patient reported outcomes and physical performance measures in participants with ACLR compared to a Control group –a cross-sectional study ... 87
4.1 Prelude to Chapter 4 ... 87
4.2 Background ... 88
4.2.1 Aim of the study ... 90
4.2.2 Hypothesis ... 90
4.3 Methods ... 90
4.3.1 Study design ... 90
4.3.2 Ethical approval ... 91
4.3.3 Study settings ... 91
4.3.4 Recruitment of participants with the ACLR and the Control group ... 91
4.3.5 Sample size estimation ... 92
4.3.6 Inclusion and exclusion criteria ... 93
4.3.7 Procedures ... 94

4.3.8 Data processing and analysis 100
4.3.9 Statistical analysis 101
4.4 Results 102
4.4.1 Data provided by ACC 104
4.4.2 Patient-reported outcomes 104
4.4.3 Muscle strength 106
4.4.4 Single-leg hop 112
4.4.5 Knee laxity in sagittal plane 112
4.5 Discussion 113
4.5.1 Patient-reported outcomes 114
4.5.2 Muscle strength 116
4.5.3 Single-leg hop 119
4.5.4 Knee laxity in the sagittal plane 120
4.5.5 Limitations 121
4.6 Conclusions 122
4.7 Summary 122
5 Participants' perspectives of the outcome of anterior cruciate ligament (ACL) reconstruction surgery: a mixed-method study. 123
5.1 Prelude to Chapter 5 123
5.2 Background 124
5.3 Methods 125
5.3.1 Study Design 125
5.3.2 Recruitment, inclusion and exclusion criteria for the study 126
5.3.3 Procedures 126
5.3.4 Data analysis 129
5.4 Results 130
5.4.1 The 'fear of re-injury' versus 'confidence' continuum 135
5.4.2 Live life normally 141
5.4.3 Need of reassurance and maintenance of knee health 143
5.5 Discussion 149
5.5.1 Methodological considerations 154
5.6 Conclusion 155
5.7 Summary 155
6 Knee biomechanics in participants with anterior cruciate ligament reconstruction compared to the Control group during stair navigation 157

6.1 Prelude to Chapter 6 157
6.2 Background 158
6.2.1 Hypothesis 160
6.3 Methods 160
6.3.1 Study design 160
6.3.2 Equipment 160
6.3.3 Procedures 162
6.3.4 Data processing and analysis 165
6.3.5 Statistical analysis 170
6.4 Results 171
6.4.1 Stair ascent 172
6.4.2 Stair descent 179
6.4.3 Repeatability of knee joint moments using the adopted biomechanical model 186
6.5 Discussion 186
6.5.1 Demographics 187
6.5.2 Spatiotemporal variables for stair ascent and descent 188
6.5.3 Joint angles 189
6.5.4 Moments 190
6.5.4.1 Ascent 1904
6.5.4.2 Descent 198
6.5.5 Methodological considerations 194
6.6 Conclusion 197
6.7 Summary 197
7 Association of knee moments with the participant-related factors. 198
7.1 Prelude to Chapter 7 198
7.2 Background 199
7.2.1 Muscle strength and the knee flexion moment 199
7.2.2 Muscle strength and knee adduction moment 200
7.2.3 Moments and their association with time since surgery 202
7.2.4 Recovery of knee moments for men and women following ACLR 203
7.2.5 Aims 204
7.2.6 Hypothesis 204
7.3 Methods 205
7.3.1 Ethical approval, Study design, setting and recruitment 205

7.3.2 Inclusion criteria for ACLR participants ... 206
7.3.3 Exclusion criteria for the ACLR group ... 206
7.3.4 Procedures ... 206
7.3.5 Data processing ... 207
7.3.6 Statistical analysis ... 207
7.4 Results ... 209
7.4.1 Descriptive results ... 210
7.1.1.1 Multiple regression for the knee flexion and adduction moment during stair ascent ... 212
7.2.1.1 Multiple regression for the knee flexion and adduction moment during stair descent ... 213
7.5 Discussion ... 216
7.5.1 Limitations ... 221
7.6 Conclusion ... 223
7.7 Summary ... 223
8 Summary and recommendations ... 224
8.1 Background ... 224
8.2 Overall summary of results ... 224
8.3 Factors influencing the clinical outcomes in patients with ACLR: A conceptual model ... 230
8.4 Implications for clinical practice ... 236
8.4.1 Optimising the knee moments following ACLR ... 236
8.4.2 Restoring knee moments symmetry ... 237
8.4.3 Need for an extended rehabilitation and the self-management of knee health ... 239
8.4.4 Need of patient education ... 240
8.4.5 Tool for assessment ... 241
8.5 Strengths of this thesis ... 241
8.5.1 Sequential design of studies ... 241
8.5.2 Mixed method approach ... 242
8.5.3 Data analysis ... 242
8.5.4 Contribution to the literature ... 243
8.6 Limitations ... 243
8.6.1 Knee-related impairments only ... 244
8.6.2 Recruitment of participants with 10-20 years post-reconstruction ... 244
8.6.3 Lack of imaging ... 245
8.6.4 Surgical factors ... 245
8.7 Recommendations for future research ... 245
8.7.1 Analysis of data using statistical parametric mapping ... 245

8.7.2 In depth exploration of knee flexion moment and quadriceps muscle strength 246
8.7.3 Patient education and exercises for long-term management 246
8.8 Conclusions 247
References 248
List of appendices 277
Appendix A1- Modified from Downs and Black 278
Appendix A2- Mean differences for peak knee angles between participants with ACLR for between- and within-group comparisons 280
Appendix B1- Final ethics approval letter from the ethical committee 282
Appendix B2- Amendment letter to the ethical committee 284
Appendix B3- Approval letter from the ethical committee to the amendment letter 285
Appendix B4- Research consultation with Maori committee 286
Appendix B5- Study flyer for recruiting the participants through Newspaper 287
Appendix B6- Study flyer for participants recruitment from community 288
Appendix B7- Participant information sheet for ACLR group 289
Appendix B8- Participant information sheet for control group 294
Appendix B9- Consent form for ACLR group 298
Appendix B10- Consent form for control group 300
Appendix B11- ACC release form 302
Appendix C1- Knee Injury and Osteoarthritis Outcome Score (KOOS) 303
Appendix C2- Tegner activity Scores 308
Appendix C3- Confidence during your sport scale 309
Appendix C4- Short Form-12 Health Survey 310
Appendix C5- History of previous injuries 312
Appendix C6- Reliability of KT-arthrometer in sagittal plane 313
Appendix C7- Data provided by Participants and Accident Compensation Corporation (ACC) .. 314
Appendix C8- Peak torque and weight data of participants with ACLR 316
Appendix C9-Time between injury and surgery 318
Appendix D1- Bracket 320
Appendix D2- Additional participant quotes 322
Appendix D3- Data check with the participants for qualitative study 331
Appendix E1- Visual 3D algorithm for determining gait events 334
Appendix E2- MATLAB code to plot the linear envelops for angles and moments 336
Appendix- F1 Assumptions of the multilinear regression- stair ascent 348
Appendix F2 Assumptions of the multilinear regression- stair descent 350

List of tables

Table 2.1. Knee laxity scores in sagittal plane 25
Table 2.2. Knee injury and osteoarthritis outcome scale (KOOS) 29
Table 2.3. Tegner activity level scale 34
Table 3.1. Keywords used for data search 40
Table 3.2 Methodological quality assessment. 46
Table 3.3 Study characteristics and variables measures at knee in included studies 51
Table 3.4. Effect sizes for joint angles between participants with ACLR for between- and within-group comparisons 69
Table 3.5. Effect sizes for moments between participants with ACLR for between- and within-group comparisons. 70
Table 4.1. Participant characteristics 105
Table 4.2. The ACLR group scored significantly worse in all five dimensions of the KOOS and Physical component of SF-12 Health survey 106
Table 4.3. Differences in muscle strength, single-leg hop, knee laxity among ACLR and Control group 110
Table 4.4. Results of post-hoc testing the ACLR and Control groups. 111
Table 5.1. Interview guide 128
Table 5.2. Participant demographics and patent-reported outcomes. 132
Table 5.3. Themes and subthemes from participant data. 135
Table 6.1. Joint angles and moments 168
Table 6.2. Outcome measures 169
Table 6.3 Participant characteristics 172
Table 6.4. Mean (SD) of spatiotemporal variables, moments and angles: stair ascent 177
Table 6.5. Results for post-hoc tests between-group and side-to-side comparisons during stair ascent 178
Table 6.6. Mean (SD) of spatiotemporal, angles, and moments: stair descent 182
Table 6.7. Results for post-hoc tests between-group and side-to-side comparisons during stair descent 184
Table 6.8. Repeatability of knee joint moments using the adopted biomechanical model 185
Table 7.1. Descriptive statistics 210
Table 7.2. Descriptive statistics for patient-reported outcomes of the ACLR cohort (n = 33) 211
Table 7.3. Mean of predictor and outcome variables of injured and uninjured sides 212

Table 7.4 Multiple regression analysis of predictors of the flexion and adduction moment of the involved limb during stair navigation. 215
Table 7.5 Model summary for the regression analysis. 215

List of figures

Figure 1.1. Research pathway 9

Figure 3.1 Flow diagram for study selection process. 45

Figure 3.2 Forest plot for peak knee flexion angle during walking, stair navigation and running compared with Control group. 72

Figure 3.3 Forest plot for peak knee adduction angle during stance phase of gait during walking compared with Control group. 73

Figure 3.4 Forest plot for peak tibial external rotation angle during stance phase of gait during walking compared with Control group. 73

Figure 3.5 Forest plot for peak tibial internal rotation angle during stance phase of gait compared with Control group. 73

Figure 3.6 Forest plot for knee flexion moment during stance phase of gait in different activities. 75

Figure 3.7 Forest plot for first peak of knee adduction moment during stance phase of gait in different activities 77

Figure 4.1. Recruitment of ACLR and Control group participants for the study. 94

Figure 4.2. Positioning and application of KT-Arthrometer 99

Figure 4.3. Flow of participants with ACLR in the study. 102

Figure 4.4. Flow of Control group participants in the study. 103

Figure 4.5. Differences in the quadriceps concentric strength between ACLR and Control group. 107

Figure 4.6. Differences in quadriceps eccentric strength between ACLR and Control group. 108

Figure 4.7. Differences in hamstring concentric strength between ACLR and Control group. 109

Figure 4.8. Group x Side interaction for the groups for hamstring concentric peak torque. 109

Figure 4.9. Differences in single-leg hop performance between ACLR and Control group. 112

Figure 4.10. Differences in knee laxity between ACLR and Control group. 113

Figure 5.1. Causes fear of re-injury and its consequences (n=8). 139

Figure 5.2. Concept of the three themes emanating from the analysis of the participant concern 148

Figure 5.3 ICF model based on the study results. 149

Figure 6.1 Camera set up for the motion capture, black outline near the force plate represents the capture volume. 161

Figure 6.2. Stair case used for data collection. Step 1 was placed over the force platform. 161

Figure 6.3. Marker set: front and side view 163

Figure 6.4. Stair ascent (1) starting position (2) foot on step 1, (3) foot on step 1 continue (4) finishing position. 164

Figure 6.5. Stair descent (1) starting position; (2) foot on step 1, (3) foot on step 1 continue (4) finishing position. 165
Figure 6.6. Global and local coordinate system 166
Figure 6.7 Linear envelopes (means and SDs) for angles and moments during the stance phase of stair ascent in participants with ACLR. 174
Figure 6.8 Diagram indicating the flexion moment asymmetry in participants with ACLR. 176
Figure 6.9 Linear envelopes (means and SDs) for angles and moments during the stance phase of stair descent in participants with ACLR. 180
Figure 7.1. Scatter plot depicting the relationship between the peak knee flexion moment and concentric quadriceps strength during stair ascent 213
Figure 8.1. Factors influencing the clinical outcomes in patients with ACLR: A conceptual model. 232

List of abbreviations

ACL:	Anterior cruciate ligament
ADL:	Activities of daily living
ACLR:	Anterior cruciate ligament reconstruction
AMTI:	Advanced Mechanical technology
ANOVA:	Analysis of variance
BMI:	Body mass index
ES:	Effect size
CI:	Confidence interval
COREQ:	Consolidated Criterion for Reporting Qualitative Research
DR:	Daniel Cury Ribeiro
HRQOL:	Health related quality of life
HT:	Hamstring tendon
ICC:	Intraclass Correlation Coefficient
KOOS:	Knee osteoarthritis outcome scale
LSI:	Limb symmetry index
MATLAB:	Matrix Laboratory
MCS:	Mental component summary
MD:	Mean difference
NZ:	New Zealand
QOL:	Quality of life
SF-12:	Short form-12 Health Survey
SD:	Standard deviation
SEM:	Standard error of measurement

STROBE:	Strengthening the Reporting of Observational studies in Epidemiology
P:	Participant
PT:	Patellar tendon
PCS:	Physical component summary
GS:	Gisela Sole
MK:	Mandeep Kaur
USA:	United States of America
VIF:	Variance inflation factor
X, Y, Z:	Vectors of global coordinate system
x, y, z:	Vectors of local coordinate system

1 Introduction

1.1 Background

Rupture of the anterior cruciate ligament (ACL) is a common injury in sports such as netball, basketball, rugby, and soccer, and is especially common among young adults. The ACL injury has an extensive impact not only on an individual, but also on their family, work, and the quality of life. Rupture to the ACL predisposes the individual to increased risk of early onset of degenerative changes (Von Porat, Roos, & Roos, 2004). Of those suffering an ACL injury, 50-70% have symptoms associated with post-traumatic osteoarthritis 10 years following the injury (Lohmander, Englund, Dahl, & Roos, 2007). As these injuries have the highest rate for people below 30 years of age, by the time they reach 40, approximately 50% of those injured individuals are likely to have signs of knee osteoarthritis. It is important to understand the potential outcomes of an ACL injury, as it is associated with high levels of impairment and represents a long-term burden on the health system and for the individual.

The ACL injuries are treated with non-surgical management or with surgery. The treatment costs of ACL injuries are high: nearly ten years ago average costs were reported to be NZ$11,157 for surgery, compared with non-surgical treatment costing NZ$885 (Gianotti & Marshall Stephen., 2009). Surgical treatment aims to allow the patient to return to sports, and to restore knee function as optimally as possible. Reconstruction of the ACL is commonly associated with two main outcomes: firstly, the risk of re-injury on return to physical activity and sport (Paterno, Rauh, Schmitt, Ford, & Hewett, 2012), and secondly, the early onset of post-traumatic osteoarthritis in the long-term (Lohmander et al., 2007). Mechanisms contributing towards both risks of re-injury and development and progression of post-traumatic osteoarthritis are multi-factorial and complex. For the the development of knee osteoarthritis, these include biomechanical, physiological, and inflammatory factors (Andriacchi, Favre, Erhart-Hledik, & Chu, 2015). Re-injury is not only associated with biomechanical aspects, but also to the level of return to physical activity and the age of the participants (Swärd, Kostogiannis, & Roos, 2010; Wiggins et al., 2016). Therefore, it is important to understand the outcomes of ACL reconstruction (ACLR).

Additionally, ACL rupture has been shown to alter gait biomechanics as indicated by joint angles and moments. Joint angles and moments are measures used to estimate suboptimal joint loading, a contributing factor towards the development of post-traumatic osteoarthritis (Foroughi, Smith, & Vanwanseele, 2009; Nigg, MacIntosh, & Mester, 2000). Lower knee flexion angles and reduced moments were reported by participants with ACLR compared with the control group at 3 years post-surgery (Hart, Culvenor, et al., 2015). It seems that knee function, along with joint angles and moments, may not be restored even mid- to long-term post-surgery (Tengman et al., 2014; Tengman, Grip, & Hager, 2013). However, there is a dearth of studies exploring the lower limb kinetics and kinematics in the mid- to long-term following ACLR.

Exploring the biomechanical outcomes without analysing the muscle function in participants with ACLR would provide incomplete information relating to joint function. Loss of thigh muscle strength has been reported up to five years after surgery in participants with ACLR (Lautamies, Harilainen, Kettunen, Sandelin, & Kujala, 2008). Contraction of the muscles helps to protect the joint from high stresses. In contrast, decreased muscle strength can increase the risk of joint damage, potentially contributing towards onset and progression of osteoarthritis (Buckwalter, 2002). Therefore, it is important to explore the recovery of muscle strength in participants with ACLR as it can influence the knee biomechanics.

Rehabilitation following ACLR aims not only to gain optimum muscle strength, but is important to restore the joint function and physical performance as well. It is possible that joint function and physical performance on the injured side are not restored optimally compared with the contralateral limb in participants with ACLR or with the uninjured control group. Understanding of joint loading, physical performance, and muscle strength-related outcomes in the mid- to long-term can help researchers to understand the aetiology of post-traumatic osteoarthritis. It will also highlight if the onset and progression of osteoarthritis are related to the presence of physical impairments and biomechanical factors following the surgery. There is a dearth of studies in New Zealand investigating overall outcomes of ACLR in the mid- to long-term (2-20 years) following surgery.

1.2 The need of mixed-method thesis

As per shifting of the health care model to more patient-centered approach, patients' beliefs and satisfaction should be explored in depth as it can provide information related to their recovery process and outcomes of surgery. Based on the International Classification of Functioning, Disability and Health (ICF) model, functioning and disability are multidimensional concepts such that a person's level of functioning is a dynamic interaction between their health conditions, environment, and personal factors (Stucki, Cieza, & Melvin, 2007). In addition, the complexity and variation in surgical techniques and rehabilitation following ACLR has made it difficult to understand the overall outcomes of the surgery. Moreover, recovery process following the episode of trauma could differ from person to person. Therefore, focus is needed on the participants' concerns regarding their knee health in the longer-term.

It has been advocated that the complex phenomenon of the health care system relating to the outcomes of a disease or a particular condition, cannot be studied simply through a single approach (Morgan, 1998). This is primarily due to the wide disparity in individuals' needs based on their age, culture, gender, level of physical activities, psychological needs, behaviours and perceptions towards their own health. Due to these individual differences, examining the outcome of a condition through a single research approach, either quantitative or qualitative, may not be appropriate for every participant. Therefore, a mixed-method approach was used in this thesis. Mixed methods provide more clarity and a deeper insight into the phenomenon under study by combining quantitative and qualitative research methods in the same project (Greene, 2007; Van Griensven, Moore, & Hall, 2014).

Qualitative methods of research are considered valuable tools to study and analyse the patients' experiences, especially for the conditions which take a long time to develop. Also, the form of data which is hard to quantify, such as verbal or non-verbal communication is studied under the qualitative research paradigm (Denzin & Lincoln, 2005). Reviewing the outcomes in the mid- to long-term following ACLR can help the health care system to improve management strategies based on the patient feedback, ultimately improving patient health. Many questions related to the physical attributes of patients' health could be answered by quantitative laboratory-based studies and using questionnaires. However, it is a daunting task to understand the reasons behind changed levels of physical functions. Therefore, defining outcomes of ACLR through mixed-methods can be an important guide to ACL injury management in the long-term.

1.3 Research question

Do physical, psychosocial, biomechanical and knee function-related impairments persist following ACLR in participants up to 20 years following surgery?

The research presented in this thesis aims to understand the nature of the physical, psychosocial, knee-function and biomechanical impairments that may result from ACLR, as well as the detrimental impact such outcomes may have on a patient's quality of life in the longer-term following surgery. While various studies have explored the short-, mid-, and long-term consequences of outcomes of ACLR, these have not yet been investigated within the New Zealand health care system. Outcomes may vary in different geographic regions because of the surgeons' choice of technique and graft, the rehabilitation protocol, and differences in patients' levels of physical activity and their lifestyle. In addition, different methodologies used in previous biomechanical studies have made it difficult to compare the variables and the outcomes of interest. Using a mixed-method approach in this thesis can highlight the physical impairments along with the impact of ACL injury on the quality of life, physical activity and behavioural changes in participants with ACLR in long-term.

1.3.1 Thesis aims

The overall aim of this thesis was to explore medium (2-10 years) to long-term (10- 20 years) outcomes of ACLR in New Zealand. The specific aims were to:

- Determine medium (2-10 years) and long-term (10-20 years) outcomes of current management of ACLR in terms of muscle strength, physical performance, knee laxity and biomechanical outcomes, with an emphasis on risk factors associated with post-traumatic osteoarthritis.
- Explore the participants' experiences of the outcomes of their surgery more than 2 years following surgery in relation to physical activity, sports, occupation and quality of life.
- Determine if there is an association between knee moments and participant-related factors such as muscle strength, time since surgery and sex of the participants.

1.3.2 Study objectives

- To systematically review the literature that investigated the knee joint angles and moments in participants with ACLR compared with their contralateral side, or an uninjured Control group, during different activities including walking, stair ascent, stair descent, and jogging (Chapter 3).
- To determine the patient-reported outcomes, muscle strength, physical performance and knee laxity in participants with ACLR from 2-10 years following surgery compared to their contralateral limb and Control group (Chapter 4).
- To determine the participants' perspectives about the outcomes of their injury, surgery, and rehabilitation in relation to physical activity, sports, occupation and quality of life (Chapter 5).
- To determine the differences in peak angles and moments in participants with ACLR from 2-10 years following surgery compared with their contralateral limb and Control group (Chapter 6).

- To determine if a significant relationship exists between knee moments following ACLR with the muscle strength, time since surgery, and sex of the participant (Chapter 7).

1.4 Research pathway

The research pathway of this thesis is structured through a series of steps as illustrated in Figure 1.1. Firstly, literature related to ACL ruptures, incidence, and its management was studied. Secondly, literature related to the recovery of participants following surgery such as muscle strength, physical performance, and knee laxity were studied. Participants' perspectives about their health condition are important to understand, therefore, their perspectives and the patient-reported outcomes were studied. This was followed by the literature related to the biomechanical outcomes following surgery. The primary literature review facilitated the need for a systematic review and meta-analysis focusing on the moments and angles in participants with ACLR compared with the uninjured Control group (Chapter 3). This review included the studies examining peak knee moments and angles on the injured side compared with the contralateral limb, or to the uninjured Control group, during walking, stair ascending, stair descending and jogging activities. Methodological insights regarding the laboratory-based cross-sectional study (Chapter 6) task and the variables were informed through this systematic review. This led to the development of the cross-sectional study comparing the peak moments and angles during stair ascent and descent in participants with ACLR compared with the contralateral limb and with the uninjured Control group 2-10 years following surgery (Chapter 6). Results of the systematic review also informed the biomechanical study to determine whether muscle strength, time since injury, and sex of the participants are predictors of peak moment in participants with ACLR. This study involved 35 participants with ACLR, and peak biomechanical variables were studied during stair ascent and descent (Chapter 7).

The literature review (Chapter 2) emphasized that the participants' perspectives relating to their recovery and quality of life following surgery as important in the recovery process. This inspired the qualitative study, which aimed to gain deeper insight into participants' perspectives 2-10 years following surgery in relation to physical activity, sports, occupation, and quality of life. A mixed method approach was undertaken for this study, using valid and reliable electronic patient-reported outcomes, followed by face-to-face interviews, to understand the influences of the surgery on their life quality of life (Chapter 5). The thesis concluded (Chapter 8) with a summary and discussion of the major findings of chapters 3, 4, 5, 6, and 7, and an assessment of the overall strengths and limitations of the thesis. This chapter also presents the conceptual model representing the factors responsible for the outcomes of the ACLR, and provides recommendations for further research.

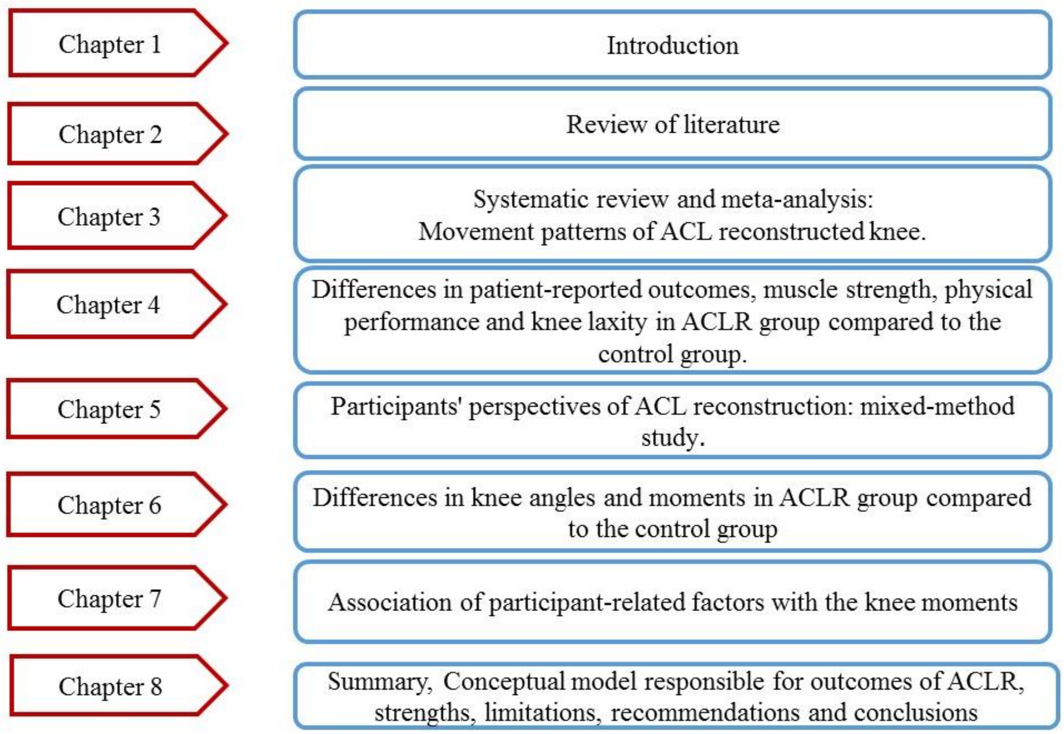


Figure 1.1. Research pathway

1.5 The significance of the research

This research contributes to defining physical and psychosocial impairments and knee function in participants with ACLR in mid- to long-term following surgery in New Zealand. It explores patient-reported outcomes along with the muscle strength, physical performance, knee laxity and knee biomechanics related-outcomes following ACLR. The mixed-method study can provide participants' perspectives about their knee health and effect of ACLR on their knee-related quality of life. The results of this thesis can be considered in research and clinical practice to improve the rehabilitation strategies and will highlight the patients' concerns in the longer-term following surgery and rehabilitation. The association between knee moments and the participant-related factors can be helpful while considering making assessments for impairments in participants with ACLR. Overall, the mixed-method research approach can provide deeper understanding of the knee-related impairments.

.

2 Literature review

2.1 Prelude to Chapter 2

This chapter provides a narrative review of the background to this thesis. Literature related to ACL injury, its management, and consequences following ACLR in the short-term and long-term are reviewed. Following that, a summary of research concerning recovery related to muscle strength, physical performance, and knee laxity is presented, supporting the aim of the thesis. This is followed by reviewing patients’ perspectives and patient-reported outcomes at different times following surgery.

Chapter 2

2.2 Background

The literature on ACLR and the recovery process following the surgery is vast. This narrative literature review focuses on 4 areas relevant to this thesis:

1. Anterior cruciate ligament rupture, incidences and management.
2. Consequences following the ACLR.
3. Recovery process following the ACLR involving muscle strength-related outcomes, physical performance, and knee laxity.
4. Patients' perspectives related to the influence of ACLR on their lives.

2.3 Anterior cruciate ligament injury and management

The ACL is an intra-articular ligament of the knee, comprised of anteromedial and a posterolateral bundle (Amis & Dawkins, 1991). The primary role of the ACL is to resist the anterior translation of the tibia, and the secondary role is to stabilise internal rotation and valgus movement and the forces of the tibia on the femur (Sakane et al., 1997). It is considered a strong ligament capable of resisting the forces as much as 2,200 N (Woo & Adams, 1990). Overall, the ACL plays an important role in the knee joint function by guiding movement and providing stability during ambulatory and functional activities.

Anterior cruciate ligament injury occurs most frequently through non-contact mechanisms (Zantop, Brucker, Vidal, Zelle, & Fu, 2007) in sports such as netball, basketball, rugby, and soccer (Gianotti., 2009; Magnussen, Carey, & Spindler, 2011). The ACL consists of two bundles, the anteriomedial and posterolateral, and injury may be partial, involving less than

50% of ligament tear (Hong et al., 2003), whereas full rupture involves tearing both the bundles (Zantop et al., 2007). ACL ruptures are treated with non-surgical rehabilitation or with surgery plus rehabilitation (Delincé & Ghafil, 2012).

According to a recent report from the USA, the overall incidence of complete isolated ACL tears were 68.6 per 100,000 person-years (Sanders et al., 2016). Eighty percent of those ACL injuries underwent surgery, which indicates the prevalence of reconstruction management (Sanders et al., 2016). That study also found a decreasing incidence of isolated ACL tears with increasing age for men, while it remained relatively stable in women (Sanders et al., 2016). In 2009 in New Zealand, the incidence of this injury was reported to be 36.9 per 100,000 person-years, with an increase to 50.1 per 100,000 person-years in 2015 (Gianotti. & Marshall Stephen., 2009). The injury represents a substantial cost for the Accident Compensation Corporation (ACC): NZ$11,157 on an average for surgical treatment for a patient (Gianotti, & Marshall Stephen. , 2009), besides the associated physical, psychological and social costs for the patient. The incidence of ACLR is unknown in New Zealand, however, among the total number of cases identified with knee injuries in five years from 2004- 2009, approximately 80% underwent surgery for torn ACL (Gianotti. & Marshall Stephen., 2009). A more recent study from New Zealand found that men who are aged between 20-29 are more frequently affected by ACL injury with 150-160 ACL reconstructions per 100,000 person-years (Janssen, Orchard, Driscoll, & van Mechelen, 2012). Based on the New Zealand ACL registry 2,933 patients underwent a primary ACLR, and 306 revision ACLR surgeries were recorded in the period of September 2015-September 2016 (NZ Orthopaedic Association, 2016). It is important to note that incidence of ACL injuries presents an increasing trend (Janssen et al., 2012), which probably will also influence the frequency of surgeries.

Surgical treatment aims to allow the patient to return to sports and restore knee function as optimally as possible. However, only 55% of these athletes are able to return to their pre-injury level of sports participation (Ardern, Taylor, Feller, & Webster, 2014). Different intrinsic and extrinsic factors play an important role in the participants' being able to return to competitive sports (Zaffagnini, Grassi, Serra, & Marcacci, 2015), however, a reduced fear of re-injury, a greater psychological readiness to return to sport and a more positive subjective assessment of knee function favour the return to sports (Ardern, 2015). Nevertheless, knee muscle weakness and altered gait patterns are common impairments that are persistent following ACLR (Brown, Palmieri-Smith, & McLean, 2009; Gokeler et al., 2013).

2.4 Consequences of Anterior cruciate ligament reconstruction

2.4.1 Re-injury of the ligament

Re-injury to the operated knee or the contralateral knee is common following ACLR (Salmon, Russell, Musgrove, Pinczewski, & Refshauge, 2005) with the reported rates between 6% to 30% (Leys, Salmon, Waller, Linklater, & Pinczewski, 2012; Wiggins et al., 2016). The second ACL re-injury rate was 15%, with an ipsilateral re-injury rate of 7% and contralateral re-injury rate of 8% (Wiggins et al., 2016). The secondary ACL injury rate (ipsilateral and contralateral) for patients younger than 25 years was 21%. These combined data indicate that nearly 1 in 4 young athletic patients who sustain an ACL injury and return to high-risk sport will go on to sustain another ACL injury at some point in their career (Wiggins et al., 2016).

Numerous factors could be responsible for the occurrence of re-injury. These include: sex of the participants, with women at higher risk (Paterno et al., 2012; Shelbourne, Gray, & Haro, 2009); time since reconstruction, with high risk in the first 24 months (Lee, Karim, & Chang, 2008; Salmon et al., 2005); and biomechanical compensatory behaviour, with the compensatory role of hip and ankle in the injured limb during different activities. Among these factors, altered biomechanics and neuromuscular function is a modifiable factor (Swärd et al., 2010). Altered movement asymmetries have been shown to be present at 12 months to 2 years following surgery (Castanharo et al., 2011; Pozzi, Di Stasi, Zeni, & Barrios, 2017), and can predispose the individuals to re-injury by asymmetric loading.

Lower limb kinetic and kinematic variables have been explored to predict the role of knee and hip moments and angles for the occurrence of injury. Different sports-related tasks have been explored in previous studies, such as single-leg horizontal hop (Elias, Hammill, & Mizner, 2015; Nyland, Klein, & Caborn, 2010; Trigsted, Post, & Bell, 2015), counter-movement jump and vertical jump (Ernst, Saliba, Diduch, Hurwitz, & Ball, 2000). These studies indicated that the moments were not similar to the Controls until 2 years following surgery, indicating the persistence of neuromuscular deficits (Trigsted et al., 2015) which may have huge implications in the biomechanics of lower limb.

2.4.2 Post-traumatic Osteoarthritis

Patients with ACL injuries are likely to have early Osteoarthritis (Lohmander et al., 2007). According to data presented by the New Zealand government, Osteoarthritis is a significant burden to society and the healthcare system (Access Economics for Arthritis New Zealand, 2010). The population affected by osteoarthritis between the ages of 15 to 64 is predicted to rise to 16.9% by year 2020 (Access Economics for Arthritis New Zealand, 2010). The literature has also highlighted osteoarthritis as the single greatest cause of disability (Brooks, 2002). Osteoarthritis is classified as primary or secondary. The reason for the development of primary osteoarthritis is idiopathic, while those for secondary osteoarthritis, injuries to joint and cartilage are major causes. Among all those who develop osteoarthritis, 20% of the overall burden arises secondary to joint injury, and is termed post-traumatic osteoarthritis (Dirschl et al., 2004).

Joint injuries increase the risk of post-traumatic osteoarthritis. It has been reported that 14% of people developed knee osteoarthritis who had a knee injury at a young age, while only 6% of those who did not have a knee injury developed Osteoarthritis (Gelber et al., 2000). Articular fractures can increase the risk of osteoarthritis up to 20-fold, and a significant ligamentous or capsular injury increases the risk of osteoarthritis up to 10-fold (Anderson et al., 2011).

The role of different factors causing early onset osteoarthritis following ACL injury and surgery are being explored. Osteoarthritis development in the injured joints is caused by intra-articular pathogenic processes initiated at the time of injury, combined with long-term changes in dynamic joint loading. The disease is initiated, and its progression caused, by a combination of endogenous and environmental risk factors. Phenotype variability is further capable of influencing the process (Lohmander et al., 2007). Variables such as re-injury, muscle strength, and body mass index also influence the outcome of the injury (Lohmander et al., 2007). Biomechanical factors (Guilak et al., 2004) could be responsible for the onset and progression of post-traumatic osteoarthritis post-ACL rupture. Mechanical loading at the joint has been extensively explored as a risk for post-traumatic osteoarthritis (Sharma et al., 1998). The optimal amount of joint loading is important for cartilage health (Griffin & Guilak, 2005); on the other hand, suboptimal loading, either the repetitive torsional stresses (Dekel & Weissman, 1978) or sudden impact load (Buckwalter, 1992), increases the risk of post-traumatic osteoarthritis. Culvenor et al., 2015 explored MRI findings of Osteoarthritis in a cohort of 111 participants with ACLR 1 year following surgery. The patellofemoral compartment was at risk for early of degeneration. Further, presence of Osteoarthritis was evident 5 years following surgery in another cohort, and was related to the lower joint loading in the frontal compartment (Wellsandt et al., 2016). It is possible that loading is not restored following initial joint injury and influences the cartilage following the surgery.

Various factors could be responsible for the onset and progression of post-traumatic osteoarthritis post-ACL rupture. For instance, raised levels of the inflammatory markers have been reported in the year following the ACL injury and surgery (Harkey et al., 2015). High levels of the inflammatory markers can lead to abnormal breakdown of the cartilage, and along with the lesser biomechanical loading of the injured leg compared to the uninjured, creating a loading asymmetry (Pietrosimone et al., 2017). Levels of inflammatory markers have been reported to be high up to 6 years following the surgery, and greater levels of matrix metalloproteinase-3 are associated with lesser knee adduction moment and the lesser vertical ground reaction force (Pietrosimone et al., 2017). The level of biomarkers has been reported to be at normal levels within 8 years following surgery (Åhlén et al., 2015). A combination of inflammation and suboptimal biomechanics can be detrimental to the joint, as both processes operate concurrently in the joint. These reviews did not mention the psychological aspect of the injury, which could influence the outcomes of surgery by influencing the attitude of the patient towards physical activity, sports and their motivation regarding exercise. Theoretically, numerous factors can be responsible for the onset and progression of osteoarthritis following such surgery.

2.5 Recovery process following the anterior cruciate ligament reconstruction

Gait analysis, muscle strength, range of motion at the joint, laxity of the graft, and physical performance tests are some of the criteria used clinically to assess joint recovery following the surgery, during rehabilitation, and to assess decisions to return to sports, recreation and occupational-related tasks. This section will summarise the recovery of muscle strength, physical performance, and knee laxity-related outcomes following the ACLR. Gait analysis in participants with ACLR will be explained in Chapter 3. Patient perspectives, which are integral for a biopsychosocial approach for rehabilitation, are discussed in this section.

2.5.1 Muscle strength-related outcomes

Muscle weakness following ACLR has been reported in various studies at different time periods following surgery, comparing the injured side to the contralateral limb or to the Control group (Keays, Bullock-Saxton, & Keays, 2000; Mattacola et al., 2002). For instance, maximal strength deficits were present at 6 months following surgery (Petersen, P. Taheri, Forkel, & Zantop, 2014) and a clear pattern of improvement in the quadriceps and hamstring strength was found from 6 to 12 months following surgery (Jong, Caspel, Haeff, & Saris, 2007).

Thigh muscle strength deficits have been reported by two systematic reviews exploring muscle strength assessments up to 24 months following surgery (Dauty, Tortellier, & Rochcongar, 2005; Xergia, McClelland, Kvist, Vasiliadis, & Georgoulis, 2011). Muscle strength differed depending on the graft used (Dauty et al., 2005; Xergia et al., 2011; Dauty et al., 2005) reported no muscle strength deficits regardless of the type of graft at 24 months. However, another systematic review indicated that muscle strength deficits may be related to the surgical graft: patients who had received a patella tendon graft were more likely to have knee extensor strength deficits, while those with hamstring grafts were likely to have flexor strength deficits (Xergia et al., 2011).

Another review exploring the muscle strength recovery following ACLR has indicated that muscle weakness at the quadriceps and hamstrings may persist from 3 months to 6 years following surgery with some inconsistent results which could be due to different methodologies used among the included studies (Petersen et al., 2014). This thesis explored the muscle strength in participants with ACLR from 2 to 10 years following surgery using the isokinetic strength tests, which is considered a ‘gold standard’ for strength testing.

A recent long-term retrospective study reported reduced peak torque of extensors concentric and eccentric muscle strength compared to the uninjured limb at more than 20 years post-ACLR compared to age-matched Controls, and when comparing the injured to uninjured sides (Tengman, Olofsson, Stensdotter, Nilsson, & Häger, 2014). Asymmetrical quadriceps strength at the time of return to sports is associated with asymmetrical knee biomechanics during hopping (Palmieri-Smith & Lepley, 2015), which in turn can predict ACL re-injury (Paterno et al., 2010). Therefore, symmetric muscle strength prior to returning to sports may be required to decrease risk of further injuries (Grindem, Snyder-Mackler, Moksnes, Engebretsen, & Risberg, 2016). Apart from the knee muscle strength deficits, hip muscle strength deficits in the hip flexors at 24 months following the surgery have also been reported (Dalton et al., 2011; Petersen et al., 2014). However, the focus of this thesis is on examining the knee-related impairments and function; therefore, hip joint muscle strength was not explored.

A number of reasons could be responsible for short to long-term persistence of muscle weakness. Factors contributing to the muscle weakness include factors such as such as pre-operative quadriceps activation and muscle strength (Lepley & Palmieri-Smith, 2016), lower activation of quadriceps muscle post-operatively (Hart, Pietrosimone, Hertel, & Ingersoll, 2010), and reduced proprioception (Bonfim, Paccola, & Barela, 2003). Reduced quadriceps function in isokinetic knee-extensor strength and lower voluntary activation was found in a study with participants at 3 years post-surgery in the involved limb compared to the uninvolved limb in the ACLR patients (Otzel, Chow, & Tillman, 2015).

The ACL injury and surgery may also influence the activation at the central nervous system. Studies have reported the changed activation of the sensory cortex (Valeriani et al., 1996), depressed cortical excitability (requiring higher level of stimulus at the motor cortex to generate quadriceps contractions) (Lepley, Ericksen, Sohn, & Pietrosimone, 2014), and neuroplasticity in the brain (Grooms, Appelbaum, & Onate, 2015). Alterations of cortical and spinal reflexive excitability pathways have been reported to affect the muscle function and overall physical performance (Pietrosimone, McLeod, & Lepley, 2012). Thus, besides peripheral mechanisms, central mechanisms of the central nervous system may also contribute towards long-term muscle strength deficits following ACLR. Probably, this is the reason that muscle strength cannot reach the pre-injury level following extensive rehabilitation.

Quadriceps weakness has been considered as a primary risk factor for knee pain, disability, and progression of joint damage in patients with osteoarthritis of the knee (Slemenda et al., 1997). Muscle weakness appears to precede the onset of symptoms related to osteoarthritis, irrespective of the reason for this weakness (Valderrabano & Steiger, 2010), and may also contribute to the development of osteoarthritis (Keays, Newcombe, Bullock-Saxton, Bullock, & Keays, 2010). Muscle weakness has been associated with joint space narrowing at 4 years following ACLR (Tourville et al., 2014) and further quadriceps weakness is a known risk factor for knee osteoarthritis (Øiestad, Juhl, Eitzen, & Thorlund, 2015). Quadriceps strength, on the other hand, has been indicated to have a protective effect against the progression of osteoarthritis (Hochberg et al., 2012; Jordan et al., 2003). Therefore, it is important to explore if any differences persist in thigh muscle strength participants with ACLR compared to the contralateral limb and to uninjured, matched controls.

2.5.2 Physical performance in participants with ACLR

Physical performance tests are included in assessments of readiness for return to physical activity and sports (Reiman & Manske, 2009). A variety of hop tests have been used to assess the limb function following surgery. These tests include single-leg hop for distance, timed hop, triple-hops for distance, and cross-over hops for distance (Noyes, Barber, & Mangine, 1991). Physical performance-based outcome measures are known to be highly reliable (Intraclass correlation coefficient 0.82 to 0.93) (Reid, Birmingham, Stratford, Alcock, & Giffin, 2007) and are practical, easy to administer and need little time to execute in clinical and research settings.

The physical performance tests are used either as a battery or as a single test to examine the limb function. These tests are often used as a clinical assessment of neuromuscular control and confidence level in the use of the limb (Borsa, Lephart, & Irrgang, 1998; De Carlo & Sell, 1997; Petschnig, Baron, & Albrecht, 1998) and are also correlated with the knee extension and flexion isokinetic strength in participants with ACLR (Laudner et al., 2015; Xergia, Pappas, & Georgoulis, 2015). Among the commonly used physical performance tests, the single-leg hop test has been widely used in research as a single test or clustered with other physical performance tests, and is known to be a reliable test (Intraclass correlation coefficient 0.76–0.97) (Palmieri-Smith & Lepley, 2015; Trigsted et al., 2015).

Following the execution of the single-leg hop tests, the distance of the hops is measured for each limb, and presented as a Limb Symmetry Index (LSI). Rationale for assessing the LSI is to assess whether the injured side reaches an acceptable level of muscle strength. Different LSI percentages have been used in previous studies. Assessing the muscle function outcome using a battery of tests or increasing the acceptable LSI level from 90% to 95% or 100% has been previously documented. A high rate of successful muscle function outcome was reported with an LSI of 80% (Thomeé et al., 2012). Therefore, it was suggested to consider the LSI percentages wisely when presenting results after ACL rehabilitation, deciding on the criteria for a safe return to sports, or designing rehabilitation programmes after ACLR (Thomeé et al., 2012).

Exploring the physical performance in the injured leg indicated the poor results when categorised by considering the LSI of 90% compared to the uninjured leg and Control group at 20 years following the surgery (Tengman, 2014). This study recruited participants who had surgery in the 1990's and had 20 years as the mean time following reconstruction. The surgical techniques have been updated many times since then, therefore, we may expect better surgical outcomes nowadays. However, this has not yet been determined. The research reported in this thesis intends to address this gap in the research. Here, the physical performance of participants 2 to 10 years following surgery are compared with age- and gender-matched controls in order to explore any deficits present in the mid-term following the surgery.

2.5.3 Knee laxity following anterior cruciate ligament reconstruction

The anteroposterior laxity of the knee joint is considered an important parameter for evaluating ACL rupture (Van Thiel & Bach, 2010). It is difficult to measure and compare the knee laxity manually, partially due to the variation in the force exerted by the examiner, and it is not possible to quantify the magnitude of tibia movement relative to the femur while performing the clinical tests such as the Lachman and Pivot Shift. The KT-1000 arthrometer is therefore a better option as it can quantify the force and the amplitude of movement. Previous studies have reported good reliability of the KT-arthrometer (Anderson & Lipscomb, 1989), but it has been questioned by others (Barcellona, Christopher, & Morrissey, 2013; Forster, Warren-Smith, & Tew, 1989). Regarding the validity using the

KT-1000 score, it may be more appropriate as a dichotomous diagnostic test with a threshold of 2 or 3 mm (Arneja & Leith, 2009). It is often used in addition to clinical examination to establish the diagnosis of ACL rupture and during the follow-up after ACLR (Aglietti, Buzzi, Giron, Simeone, & Zaccherotti, 1997).

Previous studies exploring knee laxity in participants with ACLR have presented varied results. A significant reduction in knee laxity of the injured limb 9 months to 12 months following surgery, had been reported (Semay, Rambaud, Philippot, & Edouard, 2016) (Table 2.1). Those authors suggested that the joint laxity is the product of isometric positioning of the transplant, transplant ligamentisation phenomena by collagen remodeling to mechanical stress, local muscle condition, and exposure to hormonal factors. Therefore, a return to sport without satisfactory joint control may not yield a favorable outcome. Similarly, a reduction in knee laxity was found over time after an ACLR using either a bone patellar tendon bone or hamstring graft autograft from 6 months to 7 years (Ahldén, Kartus, Ejerhed, Karlsson, & Sernert, 2009) (Table 2.1). Decrease in laxity may be due to the lack of knee extension, which has been reported in participants a few years following surgery (Sernert et al., 2002; Shelbourne, Klootwyk, Wilckens, & De Carlo, 1995). In addition, the development of early degenerative changes and secondary changes in the integrity of ligamentous tissue, as well as the soft tissue envelope, may also influence laxity.

In contrast to above studies, no differences in knee laxity were found over time from 2–6 years after ACLR using bone patellar tendon bone autografts using the KT-1000 arthrometer (Shelbourne et al., 1995), and from 7 to13 years after ACLR (Salmon et al., 2006). Differences in inter-limb knee laxity may influence physical performance (Sernert et al., 2002). The participants who displayed large side-to-side laxity differences in the sagittal plane had more deficits in flexion, extension, and functional performance during the single-leg hop test compared to those who displayed a normal side-to-side difference (Sernert et al., 2002). Therefore, for functional restoration, side to side differences may be more important among the participants rather than the laxity measurement on the injured side. Differences in the studies exploring laxity in participants with ACLR have been found regarding the amount of force and the apparatus used to measure it. So, keeping these variations in mind, we decided to use the KT-1000 arthrometer with 30lbs amount of force in this thesis to explore the side to side differences in participants with ACLR.

Table 2.1. Knee laxity scores in sagittal plane

Study	**Time since surgery**	**AP-laxity (mm) (SD)**	
		Injured side	**Uninjured side**
Semay et al, 2016	6 months	1.4 (1)	_
	9 months	1.7 (1.3)	_
	12 months	0.9 (0.5)	_
Ahlden et al, 2009	6 months	10.9 (3.2)	7.6 (3.0)
	1 year	11.3 (3.3)	10.7 (3.2)
	2 year	8.8 (4.1)	6.5 (2.6)
	7 year	7.1 (3.1)	5.7 (2.4)
Shelbourne et al, 1995	12.3 weeks	2.06 (4-9)	_
	2.7 years	2.10 (4-11)	_

mm: millimeters.

2.6 Patient-perspectives following anterior cruciate ligament reconstruction

In the patient-centred care model, the healthcare episode is an equal partnership between clinician and patient (Wilson, 2008). The patient-centred care model locates the patient centrally in the professional relationship, and supports the notion that an understanding of the patient’s perspective should underpin good practice in an equal therapeutic relationship

(Kidd, Bond, & Bell, 2011). This approach was followed in this thesis to understand the participants' perspectives following surgery.

2.6.1 Person-centred treatment approach

The physical performance measures, although critical in making clinical decisions, are not enough to fully understand the patients' experiences. Being informed about the patient experience in the management of health-related conditions is an important step to actively improve the quality of health care. A positive association between self-reported patient experiences, clinical outcomes and resource utilisation has been noted in the past (Doyle, Lennox, & Bell, 2013). Multimodal approaches to exploring patients' experiences are needed following ACLR to advance an understanding of their concerns, complaints, and outcomes of the injury, surgery and rehabilitation.

The biopsychosocial model states that health and illness are determined by a dynamic interaction between biological, psychological, and social factors leading to a given outcome. Each component on its own is insufficient to lead definitively to health or illness (George & Engel, 1980). The ICF model, as explained in Chapter 1, is based on the biopsychosocial model of disability (Stucki et al., 2007). The ICF conceptualises a person's level of functioning as a dynamic interaction between their health condition or disease, environmental factors, and personal factors (psychological and social).

Biological factors related to the outcome of the surgery have been studied extensively in terms of biomechanical variables, muscle strength, and physical performance tests as described in section 2.5. Recent studies have emphasised the role of psychological and social factors in the overall outcomes of the ACLR (Ardern, Taylor, Feller, Whitehead, & Webster, 2013). Athletes who managed to return to sport are known to have significantly higher self-esteem levels than those who do not return to sports, without observable differences in knee stability or time since surgery. Athletes in this study had higher levels of self-esteem and higher reported KOOS-QOL scores (Christino, Fleming, Machan, & Shalvoy, 2016). Similarly, in another study with 65 individuals (mean age= 22 years), higher motivation during rehabilitation was associated with returning to the pre-injury sports. Also, these participants were satisfied with their knee function 1 year after the ACLR (Sonesson, Kvist, Ardern, Österberg, & Silbernagel, 2017). A study exploring the functional outcome of surgery in 48 competitive athletes highlighted that psychosocial issues affect the overall results of the surgery with respect to return to sports. In that study, 18 showed a decrease in their level of sports. Of the 18 patients, 12 referred to fear of reinjury as the primary reason for the decrease in their level of sports reported, while persisting knee pain and instability in 6 patients were the reasons for a fall in their sporting abilities (Devgan, Magu, Siwach, Rohilla, & Sangwan, 2011).

2.6.2 Quality of life following ACL reconstruction

When exploring the outcomes of disease, it is important to investigate and evaluate the impact of the condition on patients' quality of life. Quality of life is a multidimensional concept incorporating domains related to physical, mental and emotional, and social functioning (Ferrans, 2005). Different definitions appear in the literature for health-related quality of life. Most conceptualizations of health-related quality of life emphasize the effects of disease on physical, social role, psychological or emotional, and cognitive functioning. For this thesis, the definition by Wilson and Cleary (1995, p-60) was adopted, defining quality of life as *"an individual's satisfaction or happiness with domains of life insofar as they affect or are affected by health"* page 60.

There is a gradual decrease in participants' quality of life following the surgery. Participants who were satisfied with their knee health reported less knee-related pain and symptoms (KOOS: pain and symptom scores, Table 2.2), and better quality of life (KOOS: quality of life scores) at approximately 3 years (Ardern et al., 2016) and at 5 years following surgery (Tagesson, Oberg, & Kvist, 2015). On the contrary, a systematic review indicated lowest scores in the KOOS sport/recreation function and knee-related quality of life subscales at 10 years following surgery (Magnussen, Verlage, Flanigan, Kaeding, & Spindler, 2015). This may indicate gradual decrease in quality of life over time following ACLR. In addition, exploring the quality of life at 23 years following ACLR (Tengman, 2014), KOOS quality of life scores in participants were similar to the patients with knee osteoarthritis (Aksekili et al., 2016) (Table 2.2). The ACL injury is managed by the surgery with two aims: (1) to return the participants to competitive sports in the short-term, (2) to maintain the quality of life in the long-term. Regarding the first surgical aim, it is known that only 55% of participants return to competitive sports (Ardern et al., 2014), although the percentage is higher for the elite athletes with 83% of them able to return to pre-injury level of sports following ACR (Lai, Ardern, Feller, & Webster, 2017) . The second aim for undergoing surgery, which is to maintain quality of life in the long-term, seems not to be fully achieved, as the quality of life deteriorates over time following the surgery.

Table 2.2. Knee injury and osteoarthritis outcome scale (KOOS)

Study	Time since surgery (years, mean)	Pain	Symptoms	ADL	Sport/Rec	QOL
Participants with ACLR						
Ardern et al. (2016)	3.4	93.9	86.5	98.1	85.8	78.2
Satisfied group						
Mostly satisfied	2.6	86.0	78.7	93.2	69.6	60.9
Dissatisfied group	2.6	73.1	62.0	80.7	48.4	40.6
Tagesson et al. (2015)	5	97	91	100	95	75
Magnussen et al. (2015)	10	85.8	78.9	90.5	66.1	67.6
Tengman et al. (2014)	23	78	79	84	50	49
Participants with osteoarthritis						
Aksekili et al. 2016		60	71.42	70.59	35	50

ADL: activities of daily living, QOL: quality of life, sports/rec: sports/recreation. (‘0’ indicates maximum problems, ‘100’ indicates no problem)

Numerous factors can influence the quality of life in participants with ACLR. Quality of life may be associated with psychological satisfaction with knee function (Ardern et al., 2016), preference for the competitive sports, fear of re-injury after ACLR (Filbay, Crossley, & Ackerman, 2016), and the number of injured structures (Øiestad, Engebretsen, Storheim, & Risberg, 2009). Filbay et al. (2016) conducted a qualitative study with two groups of participants with ACLR up to 20 years: those with high ACL-quality of life scores, and the second group with low ACL-quality of life scores. Participants described the importance of physically active lifestyle. Participants who avoided sport or activity reported experiencing reduced quality of life and those who overcame re-injury fears to continue sports described experiencing a satisfactory quality of life. Participants who enjoyed recreational exercise often adapted their lifestyle early after ACLR, while others described adapting their lifestyle at a later stage to accommodate knee impairments. (Filbay et al., 2016). However, this study involved participants with revision surgery and contralateral limb surgeries as well. It is known that combined injuries to the knee can influence the knee health differently by increasing the predisposition to knee osteoarthritis (Øiestad et al., 2009), and ultimately affecting the quality of life (Filbay, Ackerman, Russell, Macri, & Crossley, 2014). Furthermore, those who develop severe osteoarthritis following ACLR also reported poorer health-related quality of life compared to those without osteoarthritis (Øiestad et al., 2009). Similarly, a study with the participants from 18-45 years (mean age=28) and 3 years post-surgery reported that people who return to preinjury physical activity levels, and report higher knee-related self-efficacy and quality of life, were more likely to be satisfied with the outcome of ACLR (Ardern et al., 2016). Less than half of the participants of this study reported that they were satisfied with their knee function after surgery. This suggests a combined role of psychological factors and functional recovery for patient satisfaction after ACLR. Therefore, it is important to review the psychological and other underlying causes responsible for the poor quality of life in these participants.

Among the above-mentioned factors determining the quality of life, fear of re-injury can play a huge role in the quality of life in the longer-term (Filbay et al., 2016). Fear of re-injury was present at 2 years following surgery (Heijne, Axelsson, Werner, & Biguet, 2008) and was reported to reduce 3 years following ACLR with the restoration of the sports participation among participants (Gignac et al., 2015). Participants described their rehabilitation as an arduous experience (Scott, Perry, & Sole, 2017), their struggle with fear of injury (Gignac et al., 2015; Heijne et al., 2008) and return to sports (Gignac et al., 2015). Participants who overcome the fear of re-injury and continued their physical activities reported better quality of life than those who avoided sports and physical activities (Filbay et al., 2016). Fear of re-injury can affect the sports-performance of patients who attempt to return to their chosen activity, by reducing their confidence. Overall, fear of injury is present to a different extent in participants following surgery and has major consequences for them in their sports life.

Quality of life has been assessed with the number of tools in the literature. The type of tool used for reporting the quality of life has been found to affect the results. A review used KOOS-QOL scale to report knee-related quality of life in participants with ACLR and it was found to be low at 5 years post-surgery (Filbay et al., 2014). Another study used SF-36 Health Survey to report quality of life and indicated similar quality of life in participants with ACLR 11.5 years following surgery to the uninjured controls (Möller, Weidenhielm, & Werner, 2009). Unlike the KOOS-QOL scale, the SF-36 Health survey is a generic health questionnaire and features domains covering physical, mental, and social health. This survey addresses topics such as tiredness, sadness, and nervousness. Considering the occurrence of ACL injuries in young athletic participants, it is possible that this patient group scored higher than aged-matched, less active counterparts. Similarly, ACL-QOL has been used in the literature in some of the studies. There was a statistically significant difference between the mean ACL-QOL scores at 6, 12 and 24 months post-operatively. Patients demonstrated a statistically significant improvement in ACL-QOL score following ACLR (Heard, Lafave, Kerslake, Hiemstra, & Buchko, 2015). However, it is recommended that the ACL-QOL questionnaire be used in conjunction with currently available objective and functional outcome measures during the pre-operative, conservative and post-surgery treatment of patients with chronic ACL deficiency. Therefore, there is a need to explore the quality of life with the knee-specific questionnaire. Also, there is a need to explore the participants' experiences of the outcomes of their surgery in relation to physical activity, sports, occupation and health-related quality of life so as to determine the extent to which the ACLR has influenced their lives. The research in this thesis investigated patients' perspectives related to the effect of ACLR on their lives until 10 years following ACLR through a qualitative study. Until now, there have been no studies exploring the quality of life in participants with ACLR in the New Zealand context. The ACC funds the surgery and rehabilitation of patients with ACL injury, thus this study will potentially inform the health-care system regarding the participants' knee-related concerns and outcomes of surgery.

2.6.3 Patient-reported outcomes

To fully understand outcomes of surgery and rehabilitation, patient-reported outcomes are very important measures as they provide first-hand information relating to the patient's condition, are easy to administer, and are undemanding in terms of cost and the time involved to perform them. A number of tools exploring the patient-reported outcome measures have been used in the literature. Some of them were used in this thesis and are described below in relation to the recovery process.

2.6.3.1 The Knee Injury and Osteoarthritis Outcome Score.

The Knee Injury and Osteoarthritis Outcome scale (KOOS) has been widely used for osteoarthritis and ACL-related research: it enables analysis of knee-related outcomes such as pain, symptoms, quality of life, and knee function in daily life and sports. This scale measures the patients' opinions about their knee health and associated problems over the past week (Appendix-C1). The reliability of this questionnaire has been previously established (Roos, Roos, Lohmander, Ekdahl, & Beynnon, 1998). This questionnaire is valid for measuring the functional status and the quality of life in participants with ACLR (Salavati, Akhbari, Mohammadi, Mazaheri, & Khorrami, 2011). For patients with knee injuries, the pain, ADL, and sport/recreation subscales have adequate internal consistency, while the knee symptom and Quality of life (QOL) subscales have had reports of lower as well as adequate internal consistency (Intraclass correlation coefficient: Pain= 0.85–0.93 Symptoms= 0.83–0.95, ADL= 0.75–0.91, Sport/rec= 0.61–0.89, QOL= 0.83–0.95). KOOS has standard error of measurement from 2.2 to 3.1 among the subscales (Pain= 2.2 Symptoms= 3.1 ADL= 2.9 Sport/recreation = 2.1, QOL= 2.6). The KOOS appears to be responsive to change in patients with a variety of conditions treated with nonsurgical and surgical interventions (Bekkers, De Windt, Raijmakers, Dhert, & Saris, 2009). It has been suggested that a change of 8–10 KOOS points constitutes a clinically relevant difference (Roos & Lohmander, 2003).

2.6.3.2 The Tegner activity level scale

Tegner activity level scale involves a list of activities of daily living, recreation, and competitive sports (Tegner & Lysholm, 1985) (Appendix-C2). A score of 0-10 is assigned where 0 represents "sick leave or disability pension because of knee problems," whereas 10 corresponds to "participation in national and international elite competitive sports". Higher scores represent participation in higher-level activities. Reliability and validity of this scale has been established in individuals with ACL injury with an intraclass correlation coefficient of 0.8 and a minimum detectable change of 1 (Briggs et al., 2009).

Table 2.3 shows the potential inability of the participants to return to preinjury activity levels, following injury, surgery and rehabilitation. A review involving multiple studies indicated that participants were at 5.1 post-injury Tegner score at the mean of 10 years following surgery (Magnussen et al., 2015). There has been a decrease in the level of physical activities following surgery (Magnussen et al., 2015). Ardern et al., 2013 concludes that psychological responses before surgery, and in early recovery, were associated with returning to a pre-injury level of sport at 12 months. This report also suggested that psychological factors played a significant role in physical recovery after ACL injury and reconstruction. Apart from the physical and psychological factors related to the recovery following the surgery, other life-related events like marriage, childbirth, and increased job demands (commonly cited by non-returners) also determine whether patients return to sports or physical activities (Flanigan, Everhart, Pedroza, Smith, & Kaeding, 2013).

Table 2.3. Tegner activity level scale

Study	Time since surgery (years)	Tegner scores before injury	Tegner scores at present
Tagesson et al., (2014)	5	4 (3-5)	5 (3-7)
Tengman et al., (2014)	23	9 (3-10)	4 (3-7)
Magnussen et al, (2015)	10	-	5.1

2.6.3.3 Confidence during sports scale

The Confidence during sports scale was first devised and developed to examine the presence of fear of re-injury in a study exploring the return to sports following surgery (Ardern, Taylor, Feller, & Webster, 2012). This questionnaire consists of 8 questions relating to fear of re-injury that are scored on a 10-point scale anchored by 1 (not at all) and 10 (extremely) (Ardern et al., 2012) (Appendix- C3). Cronbach’s alpha statistic for the eight questions is 0.88 (Ardern et al., 2012). The total score is calculated by summing the individual item scores, to give a total out of 80 points, with a higher score representing a lower fear of re-injury. Athletes participating in sports following ACL injury and surgery appeared to have considerably less fear of injury and more confidence 2 to 7 years following surgery (Ardern et al., 2012).

2.6.3.4 The Short Form-12 health survey

The Short Form-12 health survey (SF-12) was designed to measure a health-related quality of life at a single time point (Ware, Kosinski, & Keller, 1996). The SF-12 is a generic measure and does not target a specific age or disease group. However, the Short Form-12 is known to provide a simple health outcome assessment following ACLR surgery at a single time point (Webster & Feller, 2014). This questionnaire explores the participant's views about their health (Appendix- C4), and has been validated in participants with ACLR. This questionnaire summarises the physical and mental components of health. Physical and Mental Health Composite Scores (PCS & MCS) are computed using the scores of twelve questions and range from 0 to 100, where a zero score indicates the lowest level of health measured by the scales and 100 indicates the highest level of health. The PCS and MCS scores tend to vary over the life span (PCS tends to decrease with age, while MCS tends to increase). This questionnaire can be self-administered and can be administered in 2 or less than 2 minutes.

2.7 Summary

Muscle strength, physical performance and knee laxity-related deficits were explored in participants following ACLR. This informed the need for an exploratory study to explore the muscle strength-related, physical performance, knee laxity, and patient-reported outcomes in participants with ACLR from 2 to 10 years following surgery (Chapter 4). Furthermore, this chapter justified the need to explore the participants' perspectives related to their physical activity, sports and quality of life following the surgery (Chapter 5).

The next chapter is a systematic review of peak knee moments and angles in participants with ACLR during walking, jogging, and stair navigation.

3 Movement patterns following ACL reconstruction: a systematic review and meta-analysis

3.1 Prelude to Chapter 3

Muscle strength deficits were reported in different studies in participants with ACLR in the literature (Chapter 2). Muscle strength deficits can alter the moments as by definition moments (or torque) are the turning effect of a force that causes angular acceleration at a specific axis (Nigg et al., 2000). Knee biomechanics is studied through exploring the knee joint angles and moments. Moments will be presented as the external moments throughout the thesis.

Lower limb kinematics and kinetics of the ACL reconstructed knee was compared to (a) the contralateral limb, and (b) healthy age-matched participants during different activities. Whether there is any change in knee angles and moments over time following ACLR was also explored. A systematic search with specific key words was run and the articles exploring the recovery of angles and moments following surgery were included. Studies with the similar variables were pooled together to generate the forest plots for meta-analysis was performed. Analysing the movement pattern helped to understand if the loading pattern of ACLR knee compared to the contralateral knee and to the uninjured control group.

Chapter 3

3.2 Background

Altered gait biomechanics can be assessed via joint angles and moments, refer to unresolved impairments following injury and surgery, and may also be a mechanical contributing factor towards the development of post-traumatic osteoarthritis (Foroughi et al., 2009; Nigg et al., 2000). Differences in these biomechanical variables appear to be important when comparing the injured side with the contralateral uninjured side in patients with ACLR and also with Control groups. Individuals with ACLR have been shown to walk with greater peak knee flexion angles compared to controls in the early phases (< 6 months), but with less flexion (more extended) after 1 year post-surgery (Hart, Culvenor, et al., 2015).

In the sagittal plane, lower external *flexion* moments were found following ACLR at mid-stance of walking at 2 to 12 months post-operatively compared to controls (Timoney et al., 1993), while no significant differences were reported on average 17 months post-surgery (Bulgheroni, Bulgheroni, Andrini, Guffanti, & Giughello, 1997). Decreased flexion moments while walking and during stair navigation have also been found in patients with knee osteoarthritis. Furthermore, a recent systematic review found increased flexion moments during walking in patients with knee osteoarthritis following joint replacements, compared to pre-operative measures (Sosdian et al., 2014). Flexion moments require an internal quadriceps moment to counteract the forces of body weight (Schmitt, Paterno, Ford, Myer, & Hewett, 2015). Decreased flexion moments are likely to indicate unloading of the knee joint or a compensatory strategy, possibly due to decreased neuromuscular control, lingering symptoms and hesitancy for weight-bearing on that side (Andriacchi, 1990).

In terms of joint loading in the frontal plane, external knee *adduction* moments are often used as the measure of load distribution in the frontal plane (Schipplein & Andriacchi, 1991). Increased peak adduction moments during walking have been associated with progression (Foroughi et al., 2009; Miyazaki et al., 2002), and severity of medial tibio-femoral compartment osteoarthritis (Sharma et al., 1998). Studies have reported conflicting results for peak adduction moments in participants with ACLR varying from low to high magnitude (Patterson, Delahunt, & Caulfield, 2014; Webster & Feller, 2012a). The status of the adduction moments in participants with ACLR needs to be explored further in mid-to long-term to understand the movement pattern.

While several studies have explored gait biomechanics following ACLR, various methodologies and tasks were used. Summarizing these gait biomechanics will increase understanding of possible impairments and guide rehabilitation interventions to improve outcome and decrease for long-term disability. Previous reviews on the recovery of gait biomechanics following ACLR have not included meta-analysis (Gokeler et al., 2013) or have analyzed only sagittal plane moments (Hart, Ko, Konold, & Pietrosimione, 2010). (Hart, Culvenor, et al., 2015) recently reviewed gait analysis only during walking activity, finding deficits in sagittal plane moments but not in the frontal plane. The current review will include other activities of daily living, namely stair ascent, descent and running, in addition to walking. It is possible that long-term impairments and asymmetries following ACLR may be more evident during those cyclical and repetitive activities that are associated with higher joint loading than walking (Kutzner et al., 2010). Thus, the primary aim of this systematic review and meta-analysis was to compare knee kinematics and kinetics in individuals with

ACL reconstruction with the contralateral limb and with healthy age-matched controls during three different tasks (walking, stair ascent/descent and running). The secondary aim was to describe the progression over time of those biomechanical variables following ACLR.

3.3 Methods

3.3.1 Search strategy and study selection

PRISMA guidelines were followed as appropriate for observational studies (Moher, Liberati, Tetzlaff, & Altman, 2009). EMBASE, Medline, Web of Science, and Scopus databases were searched from their original available dates to 1st July, 2014, with an update on the 10th August, 2015. Keywords used and the search strategy are presented in Table 3.1.

Table 3.1. Keywords used for data search

Anterior cruciate ligament	Reconstruction	Gait	Kinetics
ACL	Injury	Walking	Kinematics
Knee joint	Tear	Jogging	
	Graft	Running	
	Surgery	Locomotion	
	Deficiency	Ambulation	
		Stair climbing	
		Stair ascent	
		Stair descent	
		Stair negotiation	
		Gait analysis	

ACL: Anterior cruciate ligament. The search terms within each group were combined with the ‘OR’ operator, the ‘AND’ operator’ was used to combine the results from all four groups to obtain final yield.

The following inclusion criteria were applied: 1) Observational study designs (prospective cohort studies, case-control studies and cross-sectional studies) or randomised clinical trials

(RCT) with the comparison to control group or comparison with the contralateral uninjured side at baseline; 2) men and women, with isolated ACL ruptures or in addition to menisci and other ligamentous injury of the knee, managed with reconstructions with any type of graft; 3) studies estimating kinematic and kinetic data (discrete variables: peak angles in the three planes of movement, peak external knee flexion and adduction moments) of the ACLR knee and the asymptomatic controls during walking, stair negotiation, or running. Studies focusing on other lower limb injuries, or other tasks, such as jumping or pivoting were excluded. No language restrictions were applied. Two reviewers (MK and GS) screened all relevant titles and abstracts and were blinded to authors and journals. Full-text articles were screened according to the pre-set inclusion and exclusion criteria by the two reviewers. Any discrepancies were resolved through consensus, and a third reviewer was available if needed (DR). A manual search of the reference lists of the included articles was also conducted.

2.2 *Risk of bias within included studies*

A modified version of Downs and Black Quality Index (Downs & Black, 1998) was used to assess the risk of bias within included studies. The modified checklist included 16 questions from the following sub-groups: reporting (items 1, 2, 3, 5, 6, 7 and 10), external validity (items 11 and 12), internal validity-bias (item 15, 16, 18 and 20), internal validity-confounding (selection bias) (item 21 and 25), and power (item 27) (Appendix –A1 Modified Downs and Black quality index). Item 25 relates to confounding factors: walking or running speed were considered as the most relevant confounders, as these variables have been shown to be correlated with external knee adduction and flexion moments (Anne Mündermann, Dyrby, Hurwitz, Sharma, & Andriacchi, 2004). Thus, a score of “1” was applied if the speed of ambulation was not significantly different between participant groups, or if appropriate statistical analyses were performed, including speed as a covariate. Item 27 was reworded as "Were appropriate power calculations reported?" and the score was changed from 0 to 5 to a scale of 0 or 1. The study was assigned a score of "1" if prior power analysis was performed, with no scores being assigned in the absence of power analysis. The risk of bias assessment was performed independently by two reviewers (MK and GS), with discrepancies resolved during a consensus meeting. Kappa's correlation coefficient was calculated to determine the agreement of the scores of the individual questions for each study between the two reviewers. The modified Downs and Black Quality Index was scored out of 17. Studies with scores of 11 and above (65%) were considered to have a low risk of bias, and studies with scores below 11 were considered to have high risk of bias (Barton, Lack, Malliaras, & Morrissey, 2013).

3.3.2 **Data extraction and meta-analysis**

Data extracted from each study included sample size, participants' demographics, type of functional activities, and discrete variables for knee kinematics and kinetics (i.e. peak angles and moments during the stance phase of gait). For external adduction moments, the first of the two peaks was extracted. Peak knee tibial rotations were reported during the stance phase of gait. The corresponding authors were contacted when relevant data were not presented or were published as graphs.

Meta-analysis was performed using Review Manager v5.3 (RevMan) (Copenhagen: The Nordic Cochrane Centre, The Cochrane Collaboration, 2014) when more than one study investigated the same dependent variable during a given task using three-dimensional movement analysis. The main aim of the forest plot was to determine (standardised) mean differences and confidence intervals. Effect sizes (ES) and 95% confidence intervals (CI) were calculated for between-group (ACLR groups versus uninjured Control groups) and within-group (injured sides versus contralateral uninjured sides of the ACLR groups) comparisons of kinematic data and kinetic data. Calculated individual or pooled ES were categorised as small (<0.5), medium (≥0.5 and <0.8) or large (≥0.8) (Cohen, 1988). The level of statistical heterogeneity for pooled data was established using γ^2 and I^2 statistics (heterogeneity defined as $p<0.05$). For peak joint angles, mean differences (MD) (net difference in peak angle among any two groups) were also calculated in degrees for findings of individual studies or pooled data from two or more studies, as these may be more easily translated to clinical practice than ES.

To conduct between- and within-group comparisons of the biomechanical variables over time, the included studies were ordered in the forest plots according to 'time since surgery' (in weeks, months, or years). The shortest time since surgery was presented at the top, and the longest average time since surgery was presented at the bottom of the forest plot. This approach allowed a qualitative analysis of differences in biomechanical variables between- and within-groups over time.

3.3.3 Level of evidence

The level of evidence was defined for each variable as per Van Tulder, Furlan, Bombardier, Bouter, and Group (2003) as follows: (1) *Strong evidence* provided by pooled results derived from three or more studies, including minimum of two studies with low risk of bias, which are homogenous ($p > 0.05$); the analysis may be associated with a statistically significant or non-significant pooled results; (2) *Moderate evidence* provided by statistically significant pooled results derived from multiple studies, including at least one study with low risk of bias, which are statistically heterogeneous ($p < 0.05$); or from multiple studies with high risk of bias which are statistically homogenous ($p > 0.05$); (3) *Limited evidence* provided by results from multiple studies with high risk of bias which are statistically heterogeneous ($p < 0.05$), or from one study with low risk of bias; (4) *Very limited evidence* provided by results from one study with high risk of bias; (5) *Conflicting evidence* provided by pooled results insignificant and derived from multiple studies regardless of quality which are statistically heterogeneous ($p < 0.05$, i.e., inconsistent).

3.4 Results

3.4.1 Search results

The first search yielded 1,550 articles (Figure 3.1) and 65 remained after excluding duplicates, irrelevant titles and screening of abstracts. A further 25 studies were excluded based on the inclusion and exclusion criteria, giving a final yield of 40 studies which were included in the qualitative analysis. Thirty-seven studies were in English, two in German (Schmalz, Blumentritt, Wagner, & Gokeler, 1998; Schmalz, Blumentritt, Wagner, & Junge, 1998) and one in Chinese (Wang et al., 2009). Data from 27 studies could be included in meta-analyses.

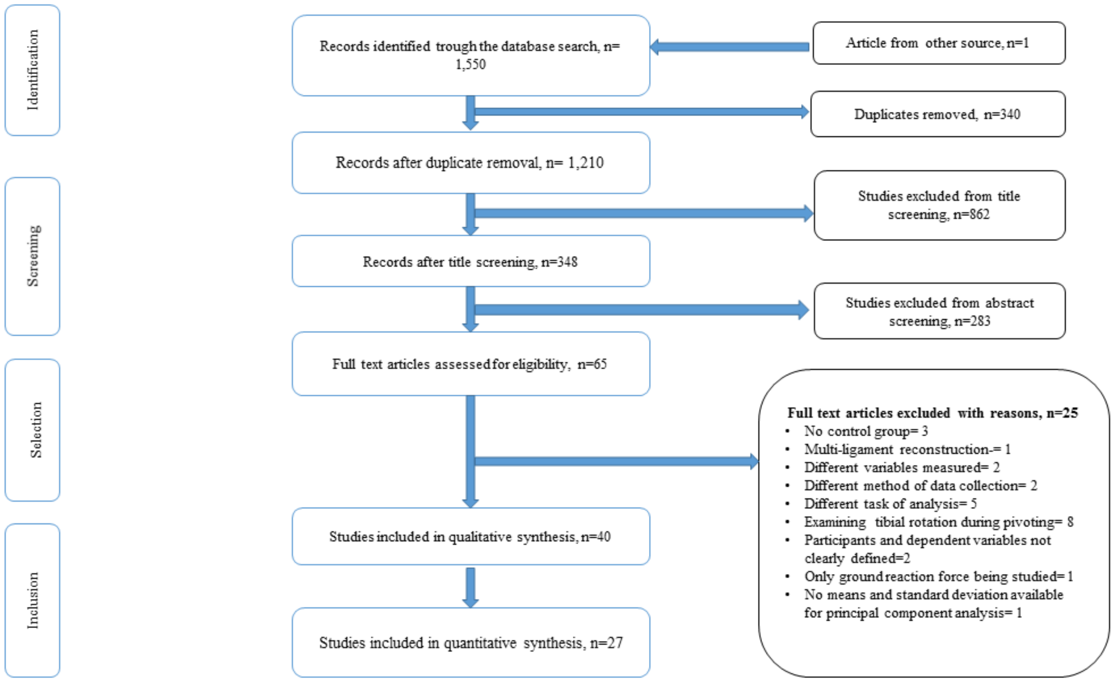


Figure 3.1 Flow diagram for study selection process.

3.4.2 Risk of bias

Kappa's correlation coefficient was 0.93 for the agreement between the two reviewers for risk of bias assessment. Twenty-six of the 40 studies were rated as low risk, and 14 as high risk (Table 3.2). Seven corresponding authors were contacted to request data for dependent variables (Butler, Minick, Ferber, & Underwood, 2009; Gao & Zheng, 2010; C. Kuenze et al., 2014; Scanlan, Chaudhari, Dyrby, & Andriacchi, 2010; Schroeder, Krishnan, & Dhaher, 2015; Varma, Duffell, Nathwani, & McGregor, 2014; H. Wang, Fleischli, & Nigel Zheng, 2012) and one provided the details (Varma et al., 2014). Variables were calculated from the figures when corresponding authors did not respond (Bush-Joseph et al., 2001; S. Di Stasi, Hartigan, & Snyder-Mackler, 2015; Roewer, Di Stasi, & Snyder-Mackler, 2011).

Table 3.2 Methodological quality assessment.

Study	**Categories and questions**																		
	Reporting							**External validity**		**Internal validity**						**Power**			
Original numbering	**(1)**	**(2)**	**(3)**	**(5)**	**(6)**	**(7)**	**(10)**	**(11)**	**(12)**	**(15)**	**(16)**	**(18)**	**(20)**	**(21)**	**(25)**	**(27)**	**Total**	**%**	**Risk of bias**
New numbering	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**	**(10)**	**(11)**	**(12)**	**(13)**	**(14)**	**(15)**	**(16)**			
Bulgheroni et al., 1997	1	1	1	0	1	0	0	U	U	U	1	0	1	1	1	0	8	47	HR
Butler et al., 2009	1	1	1	2	1	1	0	0	0	U	1	1	1	1	1	1	13	76	LR
Bush-Joseph et al., 2001	1	1	1	1	1	1	1	0	0	U	1	1	0	1	1	0	11	65	LR
Button et al., 2014	1	1	1	2	1	1	1	0	0	U	1	1	0	1	1	0	12	71	LR
Czamara et al., 2015	1	1	1	2	1	1	1	0	0	0	1	1	1	1	0	0	12	71	LR
Devita et al., 1998	1	1	1	1	1	1	0	0	0	U	1	1	0	1	0	0	9	53	HR
Di Stasi et al., 2013	1	1	1	1	1	1	1	0	0	U	1	1	1	NA	1	0	11	69	LR
Di Stasi et al., 2015	1	1	1	1	1	1	1	0	0	0	1	1	1	NA	1	0	11	69	LR
Ferber et al., 2002	1	1	1	1	1	1	0	0	0	U	1	1	0	0	0	0	9	53	HR
Ferber et al., 2004	1	1	1	1	1	1	0	0	0	U	1	1	0	1	1	1	11	65	LR
Gao and Zheng., 2010	1	1	1	1	1	1	0	U	U	U	1	1	1	1	1	0	11	65	LR
Gao et al., 2012	1	1	1	2	1	1	0	0	0	1	1	1	1	1	0	0	12	71	LR
Georgoulis et al., 2003	1	1	1	1	1	1	0	0	0	U	1	1	1	1	1	0	11	65	LR
Hall et al., 2012	1	1	1	2	1	1	1	0	0	U	1	1	1	1	1	0	13	76	LR
Hooper et al., 2001	1	1	1	1	1	1	0	0	0	U	1	1	0	NA	0	0	8	50	HR
Hooper et al., 2002	1	1	1	1	1	1	1	0	0	U	1	1	0	NA	0	0	9	56	HR
Karimi et al., 2013	1	1	1	1	1	1	1	U	U	U	1	1	0	1	1	0	11	65	LR

Study	**Categories and questions**																		
			Reporting					**External validity**				**Internal validity**				**Power**			
Original numbering	**(1)**	**(2)**	**(3)**	**(5)**	**(6)**	**(7)**	**(10)**	**(11)**	**(12)**	**(15)**	**(16)**	**(18)**	**(20)**	**(21)**	**(25)**	**(27)**	**Total**	**%**	**Risk of bias**
New numbering	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**	**(10)**	**(11)**	**(12)**	**(13)**	**(14)**	**(15)**	**(16)**			
Knoll 2004 et al.,	1	1	1	1	1	1	0	0	0	U	1	1	0	0	1	0	9	53	HR
Kowalk et al., 1997	1	1	1	1	1	1	1	0	0	U	1	1	1	1	0	0	11	65	LR
Kuenze et al., 2013	1	1	1	2	1	1	1	0	0	0	1	1	1	1	1	1	14	82	LR
Lewek et al., 2002	1	1	1	1	1	1	1	0	0	U	1	1	0	0	1	0	10	59	HR
Noehren et al.,2013	1	1	1	2	1	1	1	0	0	U	1	1	0	1	1	0	12	71	LR
Patterson et al., 2013	1	1	1	2	1	1	1	0	0	U	1	1	1	1	0	0	12	71	LR
Roewer et al., 2011	1	1	1	1	1	1	1	0	0	U	1	1	1	NA	1	0	10	69	LR
Sato et al., 2013	1	1	1	2	1	1	0	0	0	1	1	1	1	1	0	0	12	69	LR
Scanlan et al., 2010	1	1	1	1	1	1	0	0	0	0	1	1	1	1	0	0	10	56	HR
Schmalz et al., 1998	1	1	1	1	0	0	0	0	0	0	1	1	0	1	0	0	7	41	HR
Schmalz et al., 1998	1	1	1	1	0	0	0	0	0	0	1	1	0	1	1	0	8	47	HR
Schroeder et al., 2015	1	1	1	1	1	1	1	0	0	0	1	1	0	1	0	0	10	59	HR
Tellini et al., 2013	1	1	1	2	1	1	1	0	0	U	1	1	0	1	0	0	10	59	HR
Timoney et al., 1993	1	1	1	1	1	1	0	0	0	U	1	1	0	1	1	0	10	59	HR
Varma et al., 2014	1	1	1	2	1	1	1	0	0	U	1	1	0	1	1	0	12	71	LR
Wang et al., 2009	1	1	1	1	1	0	0	0	0	U	1	1	0	1	1	0	10	63	HR
Wang et al., 2012	1	1	1	1	1	1	1	0	0	U	1	1	1	1	0	0	11	65	LR

Study	Categories and questions																		
	Reporting							External validity		Internal validity						Power			
Original numbering	**(1)**	**(2)**	**(3)**	**(5)**	**(6)**	**(7)**	**(10)**	**(11)**	**(12)**	**(15)**	**(16)**	**(18)**	**(20)**	**(21)**	**(25)**	**(27)**	**Total**	**%**	**Risk of bias**
New numbering	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**	**(10)**	**(11)**	**(12)**	**(13)**	**(14)**	**(15)**	**(16)**			
Wang et al., 2013	1	1	1	1	1	1	0	0	0	U	1	1	1	1	1	1	12	71	LR
Webster and Feller, 2005	1	1	1	2	1	1	1	0	0	U	1	1	1	1	1	0	13	76	LR
Webster and Feller, 2011	1	1	1	2	1	1	1	U	U	U	1	1	1	1	1	0	13	76	LR
Webster et al., 2012	1	1	1	1	1	1	1	0	0	U	1	1	1	1	0	0	11	65	LR
Webster and Feller, 2012	1	1	1	2	1	1	0	0	0	U	1	1	1	1	1	0	12	71	LR
Zabala et al., 2012	1	1	1	1	1	1	1	0	0	U	1	1	1	1	0	0	11	65	LR

HR: High risk of bias; LR: Low risk of bias; NA: Not applicable; U: Unable to determine 1: Clear aim/hypothesis; 2: Outcome measures clearly described; 3: Patient characteristics clearly described; 4: Confounding variables described; 5: Main findings clearly described; 6: Measures of random variability provided; 7: Actual probability values reported; 8: Participants asked to participate representative of entire population; 9: Participants prepared to participate representative of entire population; 10: Blinding of outcome measurer; 11: Analysis completed was planned; 12: Appropriate statistics; 13: Valid and reliable outcome measures; 14: Appropriate case control matching; 15: Adjustment made for confounding variables; 16: Power.

3.4.3 Overview of included studies

Thirty-one studies included comparisons with asymptomatic age-matched subjects, and nine with the contralateral knee of this ACLR participant group (Table 3.3). Kinematic and kinetic variables were studied during walking in 37 studies at self-selected comfortable speed, during stair ascent and descent in eight studies (Bush-Joseph et al., 2001; Gao, Cordova, & Zheng, 2012; Hall, Stevermer, & Gillette, 2012; Hooper, Morrissey, Drechsler, Morrissey, & King, 2001; Hooper et al., 2002; Kowalk, Duncan, McCue, & Vaughan, 1997; Schroeder et al., 2015; Zabala, Favre, Scanlan, Donahue, & Andriacchi, 2013), and during running in five studies (Bush-Joseph et al., 2001; Kuenze et al., 2014; Lewek, Rudolph, Axe, & Snyder-Mackler, 2002; Noehren, Wilson, Miller, & Lattermann, 2013; Sato et al., 2013). The number of included participants ranged from 8 with ACLR and 10 controls (Kuenze et al., 2014; Lewek et al., 2002), to 45 in both groups (Zabala et al., 2013), and time since surgery from 2 weeks (Hooper et al., 2002) to 18 years (Hall et al., 2012).

A RCT conducted by (Hooper et al., 2001) was included and, for the purpose of this review, the baseline comparisons for the injured versus the contralateral uninjured knees were considered for the meta-analysis. A longitudinal cross-sectional study by (Webster, Feller, & Wittwer, 2012) was included with the results being reported at one year and 3.3 years. Data from both of these time periods were included for meta-analyses.

Grand means and standard deviations (SD) were calculated (EMathZone) where studies presented results for different groups with ACLR. In one study (Hooper et al., 2001), baseline results of participants undergoing either closed or open kinetic training were combined. Where studies compared outcomes of different surgical procedures, specifically, between hamstring and patella tendon grafts (Webster & Feller, 2011; Webster, Wittwer, O'Brien, &

Feller, 2005), single- and double-bundle grafts (Czamara, Markowska, Królikowska, Szopa, & Domagalska Szopa, 2015), and use of different portal techniques (Wang, Fleischli, & Zheng, 2013), the results of the ACLR groups were combined and compared with the controls. A study by (Lewek et al., 2002) included two groups of participants based on quadriceps strength: (1) “strong ACLR” group; (2) “weak ACLR” group. The data of these two groups were combined into a grand mean and SD. Furthermore, variables for participants with ACLR for the dominant and non-dominant limbs were combined and compared with the control group in a study by (Wang et al., 2012). Results of two groups reported by (Di Stasi, Logerstedt, Gardinier, & Snyder-Mackler, 2013), participants who passed return to sports criteria and those who did not pass, were also combined into grand means and SD, calculated from the published 95% CI. In another study by (Di Stasi et al., 2015), means and CI were estimated from the given figure and grand mean and SD for injured and uninjured sides were calculated, combining results of men and women. (Roewer et al., 2011) conducted a longitudinal study, reporting data at 6 months and at 2 years post-reconstruction. CI were estimated from the figure and SD were calculated. Data reported at both time periods were included in the forest plots (Roewer et al., 2011). Also, among the included studies only two studies performed the priori power calculations (Kuenze et al., 2014; Wang et al., 2013).

Table 3.3 Study characteristics and variables measures at knee in included studies

Study	ACLR group Characteristics	Control group Characteristics	Methodology of data collection	Task and measurable variable
Bulgheroni et al., 1997	Participants: 15 (M) Mean (SD) age: 25 (3) years Time between injury and surgery: NR Surgical procedure : BPTB Time since surgery: 17 (5) months	5 (M) 28 (3) years	4 cameras, 100 Hz Kistler force plate, 500 Hz	Walking: Natural cadence (112 ± 5.1 steps/min); footwear condition not defined. Average linear envelopes only. Kinematics: flexion/extension; adduction/abduction; internal/external rotation. Kinetics: external moments flexion/extension; adduction/abduction; internal/external rotation. Ground reaction forces: Fz, Fx, Fy
Bush-Joseph et al., 2001	Participants: 22 (13M:9F) Mean age (SD): 27 (11) years Same weight in both groups Time between injury and surgery: 8 months Surgical procedure: BPTB Time since surgery: 22 (12) months	22 (13M:9F) 29 (8) years Same weight in both groups	Multi-camera optoelectronic marker Force plate	Walking: Speed 1.18 (0.018) m/s in ACLR and 1.16 (0.016) m/s in Control group; foot wear condition not specified. Kinetics: external moment. flexion and extension. Stair climbing Kinetics: Peak external flexion moment. Running Speed 2.70 (0.39) m/s in ACLR and 2.58 (0.042) m/s in Control group. Kinetics: external flexion moment.
Butler et al., 2008	Participants: 17 (4M:13F) Mean (SD) age: 23.6 (5.8) years 24.0 (3.2) kg Time between injury and surgery: NR Surgical procedure : NR Time since surgery: 5.3 (4.4) years	No. not reported 23.4 (5.7) years 23.3 (2.4) kg	8-camera motion analysis system, 80 Hz Force plate, 1050 Hz	Walking: “Intentional” walking speed, monitored by average velocity of L5/S1 marker; neutral laboratory shoes. Kinematics: peak adduction during stance; total adduction/abduction excursion (range). Kinetics: internal moments peak abduction moment.

Study	ACLR group Characteristics	Control group Characteristics	Methodology of data collection	Task and measurable variable
Button et al., 2013	Participants: 21 (16M:5F) Mean age (SD): 29.1 (9) years 80.1 (9.5) kg Time between injury and surgery: Time since surgery: 13.5 (9) months Surgical procedure: Single bundle gracilis-ST graft	21 (12M:5F) 26.8 (7.7) years 77.6 (19.6) kg	8-camera Vicon motion analysis system, 250 Hz Kistler force plate, 1,000 Hz	Walking: 'Normal' walking speed; footwear condition not defined. Kinematics: knee flexion/extension. Kinetics: peak internal extension moment; peak external adduction moment. Gait velocity; knee 'fluency'.
Czamara et al., 2015	SB ACLR[a] Participants: 10 (M) Mean age (SD): 26 (10.22) years 82.20 (9.19) kg Time between injury and surgery: 4 (2) Time since surgery: 13.60 (3.27) months Surgical procedure: Single bundle HT graft DB ACLR[a] Participants: 13 (M) Mean age (SD): 28 (8.14) years 76.31 (11.26) kg Time between injury and surgery: 4 (2) Time since surgery: 14.08 (5.42) months Surgical procedure: Double bundle HT graft	15 (M) 23.40 (2.41) years 76.27 (7.09) kg	6-infrared camcorders, BTS SMART system, 120Hz 2 Kistler force plates, 960Hz	Walking: 'Normal' walking speed; footwear condition not defined. Kinematics: range of rotation during different stance and swing phase of gait cycle

Study	ACLR group Characteristics	Control group Characteristics	Methodology of data collection	Task and measurable variable
Devita et al., 1998	Participants: 8 (5M:3F) Mean age (SD): 20.3 years 74.2 kg Time between injury and surgery: NR Time since surgery :3 weeks, 6 months Surgical procedure: BPTB	22 (14M:8F) 21.7 years 73.7 kg	One video camera, 60 Hz Force plate, 1,000 Hz	Walking: Instructions and footwear condition not defined. Kinematics: ROM in swing; average position in stance; extensor angular impulse. Kinetics: extension/flexion joint torque; extension/flexion joint power.
Di Stasi et al., 2013	Participants: 42 (30M:12F) Mean age (SD): 29.3 (10.8) years Time between injury and surgery: 17.2 weeks Time since surgery: 6 months Surgical procedure: HT/Gracilis Allograft	Contralateral limb as controls	8-camers system, 120 Hz Force plate, 1080Hz	Walking: Self- selected comfortable speed controlled via infrared photocells; footwear condition not defined. Kinematics: flexion/extension angles. from initial contact to peak flexion Kinetics: internal joint moments and joint power.
Di Stasi et al., 2015	Participants: 39 (27M:12F) Mean age (SD): 28 (10) M: 32 (12) F years Time between injury and surgery: NR Time since surgery: 6 months Surgical procedure: HT Allograft	Contralateral limb as controls	8-camers system, 120 Hz Force plate, 1080Hz	Walking: Self- selected comfortable speed controlled via infrared photocells; footwear condition not defined. Kinematics: joint excursions during mid-stance Kinetics: internal joint extension moment
Ferber et al., 2002	Participants: 10 (5M:5F) Mean age (SD): 27.7 (9.1) years 79.1 (13.8) kg Time between injury and surgery: NR Time since surgery: 3 months Surgical procedure: BPTB	10 (5M:5F) 24.4 (3.1) years 67.2 (10.7) kg	4 cameras, 120 Hz Force plate	Walking: Self- selected comfortable speed controlled via metronome; footwear condition not defined. Kinematics: flexion/extension angles. Kinetics: flexor/extensor joint moments; power. Ground reaction forces: Fz, Fx, Fy.

Study	ACLR group Characteristics	Control group Characteristics	Methodology of data collection	Task and measurable variable
Ferber et al., 2004	Participants: 10 (5M:5F) Mean age (SD): 27.7 (9.1) years 79.1 (13.8) kg Time between injury and surgery: NR Time since surgery: 3 months Surgical procedure: BPTB	10 (5M:5F) 24.4 (3.1) 67.2 (10.7) kg	4 cameras, 120 Hz Force plate, 1200Hz	Walking: Self-selected comfortable speed controlled via metronome; footwear condition not defined. Kinematics: average flexion/extension angles. Kinetics: extensor moments/ extensor angular impulse; work and power.
Gao et al., 2012	Participants: 12 (10M:2F) Mean age (SD): 24.8 (6.1) years 83.2 (16.0) kg Time between injury and surgery: Time since surgery: 3 (12) months Surgical procedure: 6 HT 4 BPTB 2 Achilles tendon	12 (10M:2F) 23.3 (2.5) years 78.8 (15.8) kg	11- Eagle camera motion capture system, 60 Hz Force plate	Stair ascent/descent: Self-selected comfortable speed; barefooted. Kinematics: flexion, internal rotation, varus; peak and total flexion/extension; varus/valgus IE rotation peak for ascent and for descent; Mean curves for flexion/extension, varus/valgus, axial rotation for ascent and for descent. Spatiotemporal variables: stance/swing time; total time; 1st and 2nd single and double support; CTO/CFS/ TO.
Gao and Zheng 2010	Participants: 14 (12M:2F) Mean age (SD): 25.1 (5.9) years 82.5 (15.0) kg Time between injury and surgery: NR Time since surgery: 3 (12) months Surgical procedure: 7 HT 5 BPTB 2 Achilles tendon	15 (12M:3F) 22.8 (2.6) years 76.8 (16.4) kg	11-camera stereo photogrammetric system, 60 Hz 2 force plate	Walking: Self-selected comfortable speed; barefooted. Kinematics: flexion, tibial internal rotation, varus angles during static standing posture; mean curves for knee flexion/extension; varus/valgus, axial rotation, and for translation in the three planes. Spatiotemporal variables: step and stride length; step and stride speed; 1st and 2nd single and double-support phase.
Georgoulis et al., 2003	Participants: 21 (19M:2F) Mean age (SD): 25 (4) years 69.11 (7.89) kg Time between injury and surgery: NR Time since surgery : 30 (16.9) weeks Surgical procedure: BPTB	10 (8M:2F) 24.7 (3.7) years 62.1 (12.38) kg	6 cameras, 50 Hz	Walking: Self-selected pace; footwear condition not defined. Kinematics: flexion at TO and HS; max flexion during swing and loading response; max tibial abduction/adduction; max tibial IE rotation. Spatiotemporal: cadence; average gait velocity.

Study	ACLR group Characteristics	Control group Characteristics	Methodology of data collection	Task and measurable variable
Hall et al., 2012	Participants: 15 (7M:8F) Mean age (SD): 26 (6) years 75 (15) kg Time between injury and surgery: NR Time since surgery: 6 (2 -18) years Surgical procedure: 41% HT 41:Patellar tendon 12% cadaver + hamstring 6% HT	17 (7M:10F) 26 (4) years 65 (12) kg	8-Camera 3D motion analysis system, 160 Hz Force plate, 1600 Hz	Walking: Self- selected pace, with preferred shoes. Kinematics: initial flexion angle. Kinetics: peak internal extension moment; peak external varus moment. Stair ascent/descent: Kinematics: initial flexion angle. Kinetics: peak extension moment; peak varus moment.
Hooper et al., 2001	CKC group[a] Participants: 18 (13M:5F) Mean age (SD): NR 75.1 (12.3) kg Time between injury and surgery: 50.3 (61.8) months Time since surgery: 2 weeks Surgical procedure: BPTB OKC group[a] Participants: 19 (16M:3F) Mean age (SD): NR 77.4 (15.3) kg Time between injury and surgery: 34.1 (30.4) months Time since surgery: 2 weeks Surgical procedure: BPTB	Contralateral limb as controls	3 cameras, 50 Hz Force plate, 200 Hz	Walking: Gait speed and footwear not specified. Kinematics: flexion at HS, TO, MS excursion. Kinetics: concentric /eccentric energy; flexor/extensor impulse; flexion/extension moment. Stair ascent: Kinematics: flexion at HS Kinetics: peak extensor moment; extensor impulse; peak concentric power; concentric energy. Stair descent: Kinematics: flexion at HS Kinetics: peak extensor moment; extensor impulse; peak eccentric power; eccentric energy.

Study	ACLR group Characteristics	Control group Characteristics	Methodology of data collection	Task and measurable variable
Hooper et al., 2002	ACL-6 group[b] Participants: 8 (5M: 3F) Mean age (SD): 33.4 (11.0) years 77.4 (14.7) kg Time between injury and surgery: NR Time since surgery: 6 4 (0.5) months Surgical procedure: 6 BTB, 2 BTB with LAD ACL-12 group[b] Participants: 9 (4M:5F) Mean age (SD): 34.2 (10.4) years 71.1 (15.7) kg Time between injury and surgery: NR Time since surgery: 11.9 (0.6) months Surgical procedure: 5 BTB, BTB with LAD	Contralateral limb as controls	3 infrared cameras, 50 Hz Force plate, 200 Hz	Walking: Gait speed and footwear condition not specified. Kinematics: flexion at HS, TO; MS excursion. Kinetics: peak external flexion/extension/ varus moment; peak concentric power during MS. Stair ascent: Kinematics: flexion at toe contact and TO. Kinetics: peak external flexion/varus moment; peak concentric power. Stair descent: Kinematics: flexion at toe contact and TO. Kinetics: peak external flexion /varus moment; peak eccentric power.
Karimi et al., 2013	Participants: 15 (sex not defined) Mean age (SD): 33 (2.6) Time between injury and surgery: NR Time since surgery: 6 months Surgical procedure: Combined HT and peroneus longus tendon	15 (sex not defined) 32 (3) years, weight and sex matched Control group	7 cameras Force plate	Walking: Self-selected normal walking speed; foot wear not specified. Kinematics: hip, knee, ankle and pelvis range of motion in three planes Kinetics: knee flexion/ extension moment, adduction moment, internal and external rotation moment Spatiotemporal gait. Stride length, speed and cadence Ground reaction force

Study	ACLR group Characteristics	Control group Characteristics	Methodology of data collection	Task and measurable variable
Knoll et al., 2003	Participants: 16 (9M:7F) Mean age (SD): 39.71 (2.10) M: 30.31 (10.48) F years 88.10 (20.2) M: 62.11 (8.38) F kg Time between injury and surgery: 12 days & 28.2 months Time since surgery: 12 months Surgical procedure: BPTB	51 (31M:20F) 28.17 (7.69) M:25.09 (4.21) F years 77.89 (11.88) M: 59.86 (6.38) F kg	Ultrasound based zebris,100 Hz Force plate	Walking (on treadmill): 0.83m/s; barefoot. Kinematics: peak flexion/extension. Spatiotemporal: step length; walking base.
Kowalk et al., 1997	Participants: 7 (5M:2F) Mean age (SD): 18-38 years Time between injury and surgery: NR Time since surgery: 6 (3.2 to 11.3) months Surgical procedure: BPTB	10 (6M:4F) 20-49 years	4 camera, 60 Hz Kistler force plate, 60 Hz	Stair ascent: Freely selected speed, barefoot. Kinematics: maximum joint excursion. Kinetics: internal moments Power; work.
Kuenze et al., 2013	Participants: 20 (11M:9F) Mean age (SD): 22.7 (5.2) years 72.7 (13.7) kg Time between injury and surgery: NR Time since surgery: 33.9 (23.4) months Surgical procedure: 11HT, 9BPTB	23 (12M:11F) 21.9 (3.6) years 69.6 (13.8) kg	12 cameras, 250Hz Force plate imbedded in treadmill, 1000Hz	Running: 2.68m/s, footwear condition not specified. Kinematics: external hip, knee and ankle kinematics during stance and swing phase of the gait in sagittal and frontal plane. Kinetics: external hip, knee and ankle flexion moments during stance and swing phase of the gait in sagittal and frontal plane.

Study	ACLR group Characteristics	Control group Characteristics	Methodology of data collection	Task and measurable variable
Lewek et al., 2002	Strong ACLR[a] Participants: 8 (5M:3F) Mean age (SD): 21.4 (6.0) years Time between injury and surgery: NR Time since surgery:14.3 (2.4) weeks Surgical procedure: ST- gracilis graft Weak ACLR[a] Participants: 10 (4M:6F) Mean age (SD): 25 (7.8) years Time between injury and surgery: NR Time since surgery:20.8 (9.4) weeks Surgical procedure: ST- gracilis graft	10 (8M:2F) 32.2 (6.6) years	6 camera, 120 Hz Force plate, 960 Hz Isokinetic dynamometer	Walking: Free speed, velocity monitored with photoelectric beam; footwear condition not defined. Kinematics: initial contact; peak flexion. Kinetics: peak internal flexion moments. Running: Free speed, velocity monitored with photoelectric beam. Kinematics: initial contact; peak flexion. Kinetics: peak internal flexion moments.
Noehren et al., 2013	Participants: 20 (F) Mean age (SD): 25 (6.2) years 64 (8.2) kg Time between injury and surgery: NR Time since injury: 5.2 (3.2) years Surgical procedure: 8HT 7BPTB, 5 autograft	20 (F) 26 (5.1) years 61 (5.1) kg	15 camera motion analysis system, 200 Hz. Force plate, 1200 Hz	Walking: 1.5 m/s Kinematics: flexion Kinetics: impact force, Average loading rate, extensor moment, ground reaction forces: Fz, Fx, Fy Run: 2.9 m/s Kinematics: flexion Kinetics: impact force, Average loading rate, extensor moment, ground reaction forces: Fz, Fx, Fy

Study	ACLR group Characteristics	Control group Characteristics	Methodology of data collection	Task and measurable variable
Patterson et al., 2014	Participants: 17 (3M:14F) Mean age (SD): 23.7 (3.12) years 64.9 (9.02) kg Time between injury and surgery: NR Time since injury: 3.50 (3.25) years Surgical procedure: 8HT 9BPTB	17 (F) 20.8 (1.17) years 64.7 (7.06) kg	3 cameras, 200Hz 2 force plate, 1000 Hz CODA motion analysis system	Walking: Self-selected 'normal' walking speed; barefoot. Kinematics: transverse, sagittal and frontal angles throughout entire stride. Kinetics: external peak adduction moment.
Roewer et al., 2011	Participants: 26 (18M:8F) Mean age (SD): 29.6 (10.7) years Time between injury and surgery: NR Time since surgery: 24 months Surgical procedure: Semitendinosus-gracilis graft Allograft	Contralateral limb as controls	8 cameras, 120 Hz Force plate , 1080 Hz	Walking: Self-selected 'normal' walking speed controlled via infrared photo cells Kinematics: peak flexion angle, excursion angle Kinetics: internal knee extensor moment, power
Sato et al., 2012	Participants: 7 (3M:4F) Mean age (SD): 21.3 (4.9) years 59.0 (4.7) kg Time between injury and surgery: NR Time since surgery: 14.3 (1.8) months Surgical procedure: HT	Contralateral limb as controls	9 Cameras, 200 Hz Force plate KT-1000 arthrometer	Walking: Gait speed not specified; barefoot. Kinematics: maximum internal rotation angle. Running: Gait speed not specified; barefoot. Kinematics: maximum internal rotation angle.

Study	ACLR group Characteristics	Control group Characteristics	Methodology of data collection	Task and measurable variable
Scalan et al., 2010	Participants: 26 (11M:15F) Mean age (SD): 31 years 68 kg Time between injury and surgery: NR Time since surgery: 24months (7-65) Surgical procedure: 12 allograft (9 Achilles, 1 BPTB,2 soft tissue allograft) 12 autograft (10BPTB:4HT)	Contralateral limb as control	Optoelectronic motion capture system, 120Hz Force plate	Walking: Self-selected normal walking speed; foot wear not specified. Kinematics: IE rotation; VV rotation; flexion.
Schmalz et al., 1998	Participants: 26 (M:F NR) Mean age (SD): 29 (6) years 76 (10) kg Time between injury and surgery: NR Time since surgery: 8 to 52 weeks Surgical procedure: BPTB	30 (M:F NR) 28 (5) years 71 (9) kg	Optoelectronic motion capture system, 4 cameras, 100 Hz 2 Kistler force plates, 400 Hz	Walking: Fast pace, footwear condition not specified. Kinematics: flexion/extension Kinetics: flexion/extension
Schmalz et al., 1998	Participants: 35 (M:F NR) Mean age (SD): 27 (7) years 76 (12) kg Time between injury and surgery: NR Time since surgery: 8 to 52 weeks Surgical procedure: BPTB	30 (M:F NR) 28 (5) years 71 (9) kg	Optoelectronic motion capture system, 4 cameras, 100 Hz 2 Kistler force plates, 400 Hz	Walking: Fast pace, footwear condition not specified. Kinematics: flexion/extension Kinetics: flexion/extension

Study	ACLR group Characteristics	Control group Characteristics	Methodology of data collection	Task and measurable variable
Schroeder et al., 2015	ACLR (HT) group[a] Participants: 10 (sex not defined) Mean age (SD): 32.6 (8) years 74.6 (7.4) kg Time between injury and surgery: NR Time since surgery: 9.4 (3.7) months Surgical procedure: HT ACLR (PT) group[a] Participants: 6 Mean age (SD): 30.8 (5.5) years 74.8 (18) kg Time between injury and surgery: NR Time since surgery: 9.7 (4.3) months Surgical procedure: PT	9 age matched (sex not defined) 27.2 (3.7) years 67.1 (13.4) kg	Passive motion capture system, 8 cameras, 120 Hz 3 force plates	Walking: Speed and footwear condition not specified. Kinematics: flexion/extension, abduction/adduction and rotation. Kinetics: peak flexion/extension, adduction/abduction and rotation moment Stair descent (step to floor): Kinematics: Speed and footwear condition not specified. Kinetics: peak flexion/extension, adduction/abduction and rotation moment Stair descent (step to descent) Kinematics: Speed and footwear condition not specified. Kinetics: peak flexion/extension, adduction/abduction and rotation moment
Tellini et al., 2013	Participants: 8 (5M:3F) Mean age (SD): 25.5 (7.1) years 61.3 (27.1) kg Time between injury and surgery: NR Time since surgery: 32 (6) days	8 Age, sex matched.	Video camera, 60Hz	Walking: Self-selected comfortable speed; footwear not specified; walking on floor and on a foam mat Kinematics: knee angular displacement. Spatiotemporal: stride length.
Timoney et al., 1993	Participants: 10 (M) Mean age (SD): 20-30 years Time between injury and surgery: 30 (1-66) months Time since surgery: 10 (9-12) months Surgical procedure: BPTB	10 Similar controls	Vicon motion analysis system, 200 Hz Force plate	Walking: Free walking speed; barefoot. Kinetics: ground reaction loading rate; maximally vertically directed loading rate; tibially directed loading rate; heel strike external knee moment; midstance external flexion moment. Spatiotemporal: pre heel strike foot velocities; average walking velocity.

Study	ACLR group Characteristics	Control group Characteristics	Methodology of data collection	Task and measurable variable
Varma et al., 2014	Participants: 12 (9M:3F) Mean age (SD): 30.5 (8.68) years 75 (11.13)kg Time between injury and surgery: Time since surgery: 4.5 (3.5) years Surgical procedure: BPTB	12 (9M:3F) 24.8 (8.81) years 71.6 (11.2) kg	3-DGA, 10 cameras, 100 Hz Force plate ,1000 Hz	Walking: Self-selected speed, barefoot. Kinetics: peak adduction, flexion and extension moment Walking: Uphill/downhill: Self –selected speed, barefoot. Kinetics: peak adduction, flexion and extension moment
Wang et al., 2009	Participants: 29 (18M:11F) Mean age (SD): M: 32.7 (4.6) years: F: 30.2 (9.4) years M: 75.3 (9.1) kg: F: 55.0 (7.1) kg Time between injury and surgery: 2.6 months (2 weeks – 16 months) Time since surgery: NR Surgical procedure: HT	58 (36M:22F) 31.2 (5.2) years 70.1 (24.2) kg	8-camera motion analysis system, 60 Hz, Measured before surgery, 3, 6, 9, 12 months after surgery	Walking: Walking speed of 0.52m/s; Footwear condition not specified. Kinematics: knee joint movement angle; knee joint angular acceleration; ACL relative motion parameters Spatiotemporal variables: step length; step width

Study	ACLR group Characteristics	Control group Characteristics	Methodology of data collection	Task and measurable variable
Wang et al., 2012	Group-d[a] Participants: 19 (12M:7F) Mean age (SD): 32.4 (8.6) years 83.9 (18.8) kg Time between injury and surgery: NR Time since surgery: 14.1 (4.4) months Surgical procedure: HT (16) BTB (3) Group –n[a] Participants: 22 (12M:10F) Mean age (SD): 31.1 (8.0) years 81.4 (16.4) kg Time between injury and surgery: NR Time since surgery: 13.9 (5.5) months Surgical procedure: HT (19) BTB (3)	20 (13M:7F) 23.4 (3.0) years 70.8 (13.2) kg	10 camera, 60 Hz Force plate	Walking: Self-selected speed; footwear condition not specified. Kinematics: rotations/translations. Kinetics: external adduction moment.

Study	ACLR group Characteristics	Control group Characteristics	Methodology of data collection	Task and measurable variable
Wang et al., 2013	TT[a] Participants: 12 (7M:5F) Mean age (SD): 32.75 (7.2) years 83.0 (16.7) kg Time between injury and surgery: NR Time since surgery: 17.1 (10.6) months Surgical procedure: HT AMP[a] Participants: 12 (7M:5F) Mean age (SD): 29.6 (7.2) years 85.6 (16.5) kg Time between injury and surgery: NR Time since surgery: 8.8 (4.3) months Surgical procedure: HT	20 (15M:5F) 26.3 (7.7) years 81.6 (15.5) kg	10 cameras, 60Hz 2 force plate, 1200 Hz	Walking: Self-selected walking speed 1.10 to 1.37 m/s for Control group, 0.92 to 1.45m/s for ACLR group. Footwear condition not specified; Kinematics: At neutral stance: flexion/varus; femoral external rotation. During walking: AP/ML/Superior-inferior ROM; peak valgus and external rotation. Spatiotemporal: step and stride length; step and stride speed.

Study	ACLR group Characteristics	Control group Characteristics	Methodology of data collection	Task and measurable variable
Webster and Feller, 2005	HT Participants: 17 (16M:1F) Mean age (SD): 26.8 (8) years 79.6 kg Time between injury and surgery: 10.6 (8.3) weeks Time since surgery: 9.3 (2.2) months Surgical procedure: HT PT Participants: 17 (16M:1F) Mean age (SD): 23.8 (5) years 78.9(6) kg Time between injury and surgery: 12.8 (11.7) weeks Time since surgery: 11.0 (1.9) months Surgical procedure: PT	17 (16M:1F) 24.7 (5) years 74.8 (12) kg	6-camera Vicon motion analysis system , 50 Hz Force plate, 400 Hz	Walking: Self-selected comfortable speed; barefoot. Kinematics: maximum flexion/extension; flexion at HS. Kinetics: peak torque; max flexion/extension moment; extension moment at FS.

Study	ACLR group Characteristics	Control group Characteristics	Methodology of data collection	Task and measurable variable
Webster and Feller, 2011	HT[a] Participants: 18 (16M:2F) Mean age (SD): 26.6 (6) years 79.3 (7.2) kg Time between injury and surgery: 11 (8.2) weeks Time since surgery: 9.0 (2.4) months Surgical procedure: HT PT[a] Participants: 18 (17M:1F) Mean age (SD): 23.8 (6) years Time between injury and surgery: 12.7 (11.6) weeks Time since surgery: 10.9 (2) months Surgical procedure: PT	18 (16M:2F) 24.7(5) years 74.5 (12.7) kg	6-camera Vicon motion analysis system , 50 Hz Markers (Plug in gait) Force plate	Walking : Self-selected comfortable speed; footwear condition not defined Kinematics: varus/valgus rotation; internal/external rotation.
Webster et al., 2012	Participants: 16 (13M:3F) Mean age (SD): 26 (6) years 82 (11) kg Time between injury and surgery: NR Time since surgery: 3.3 (0.4) years Surgical procedure: 2PT 14 HT	Contralateral limb as controls	Vicon motion analysis system, 50 Hz Kistler force plate	Walking: Self-selected speed; footwear condition not specified. Kinematics: flexion; varus; internal rotation. Kinetics: external moments flexion; extension; adduction.

Study	ACLR group Characteristics	Control group Characteristics	Methodology of data collection	Task and measurable variable
Webster and Feller, 2012	HT group[a] Participants: 16M Mean age (SD): 27.5 (6) years 79.5 (7) kg Time between injury and surgery: 10.7 (9) weeks Time since surgery: 9.4 (3) months Surgical procedure: HT PT group[a] Participants: 16M Mean age (SD): 23.8 (6) years 79.2 (6) kg Time between injury and surgery: 11.9 (11) weeks Time since surgery: 11.2 (2) months Surgical procedure: PT	16M 25.0 (5) years 75.9 (12) kg	Vicon motion analysis system Kistler force plate	Walking: Self-selected speed; barefoot. Kinematics: peak adduction angle. Kinetics: external peak adduction moment; vertical ground reaction force.
Zabala et al., 2012	Participants: 45 (26M:19F) Mean age (SD): 29.5 (6.1) years 74.4 (12.4) kg Time between injury and surgery: 2.2 (0.4-8.0) months Time since surgery: 26 months (22-36) Surgical procedure: Achilles tendon	45 (26M:19F) 30.2 (4.68) years 74.2 (12.3) kg	Optoelectronic motion capture system, 120 Hz Force plate	Walking: Self-selected speed, footwear condition not specified. Kinetics: (1^{st} and 2^{nd} peak) adduction external moments; abduction /adduction; flexion/extension; external /internal rotation moments. Stair ascent/descent Kinetics: (1^{st} and 2^{nd} peak) adduction external moments; abduction /adduction; flexion/extension; external /internal rotation moment.

ACL: Anterior cruciate ligament ; ACLR: Anterior cruciate ligament reconstruction; [a]: Groups combined for meta-analysis; [b]: Both groups considered separately for meta-analysis; AP: Anterior posterior; AMP: Anteromedial portal; BPTB: Bone patellar tendon bone; BTB: Bone patellar tendon bone; CKC: Close kinetic chain; CTO: Contralateral toe off; CFS: Contralateral foot strike; DB: Double bundle; DGA: Dimensional gait analysis; Fz: Vertical forces; Fx: Horizontal antero-posterior forces; Fy: Medio-lateral forces; F: Female; FS: Foot strike HS: Heel strike; HT: Hamstring tendon; IE: Internal-external; LAD: Ligament augmentation device; L5:Lumbar 5 vertebral level; M: Male; ML: Medio-lateral; MS: Mid-stance; Max: maximum; NR: Not reported; OKC: Open kinetic chain; PT: Patellar tendon; ROM: Range of motion; S1: Sacrum 1 vertebral level; SB: Single bundle; SD: Standard deviation; ST: Semitendinosus; TO: Toe off; TT: Transtibial; NR: Not reported; VV: Varus-valgus.

3.4.4 Meta-analyses

Meta-analyses were conducted for peak angles and moments (peak knee flexion and adduction moments) during the stance phase of gait (Figure 3.2 to 3.7). Tables 3.4 and 3.5 provide the ES and CI for the meta-analyses and for variables that were explored in one or more studies. Mean differences for joint angles are provided in the appendix A2.

Table 3.4. Effect sizes for joint angles between participants with ACLR for between- and within-group comparisons

Variable	Task	Comparison	Level of evidence	Studies	ES (95%CI)
Flexion angle	Walking	Controls	Strong	Four LR (Georgoulis, Papadonikolakis, Papageorgiou, Mitsou, & Stergiou, 2003; Hall et al., 2012; Noehren et al., 2013; Webster et al., 2005), two HR (Ferber, Osternig, Woollacott, Wasielewski, & Lee, 2002; Lewek et al., 2002) studies; I^2 = 48%, p=0.08	-0.2 (-0.5 to 0.1)
		Contralateral limbs	Moderate	Four LR (Di Stasi et al., 2013; Hall et al., 2012; Roewer et al., 2011; Webster, Feller, et al., 2012) , one HR (Hooper et al., 2001) studies; I^2= 83%, p <0.001	-0.6 (-0.8 to -0.4)
	Stair ascent	Controls	Moderate	Two LR (Gao et al., 2012; Hall et al., 2012) studies; I^2= 8%, p=0.30	-0.0 (-0.6 to 0.5)
		Contralateral limbs	Limited	One LR (Hall et al., 2012) study	-0.2 (-0.98 to 0.5)
	Stair descent	Controls	Moderate	Two LR (Gao et al., 2012; Hall et al., 2012) studies; I^2= 81%, p=0.02	-0.5 (-1.0 to 0.0)
	Running	Controls	Moderate	One LR (Noehren et al., 2013), one HR (Lewek et al., 2002) studies; I^2=11%, p=0.29	-0.5(-0.9 to 0.0)
Adduction angle	Walking	Controls	Moderate	Three LR (Butler et al., 2009; Georgoulis et al., 2003; Webster & Feller, 2012a) studies; I^2 = 73%, p = 0.03	-0.5 (-1.7 to 0.7)
Tibial external rotation angle	Walking	Controls	Strong	Three LR (Czamara et al., 2015; Georgoulis et al., 2003; Wang et al., 2013) studies; I^2=68%, p = 0.04	0.2 (-0.2 to 0.6)
	Stair ascent	Controls	Limited	One LR (Gao et al., 2012) study	-0.7 (-1.5 to 0.2)
	Stair descent	Controls	Limited	One LR (Gao et al., 2012) study	-1.1 (-2 to -0.2)
Tibial internal rotation angle	Walking	Contralateral limbs	Strong	Three LR (Sato et al., 2013; Webster & Feller, 2011; Webster, Feller, et al., 2012) studies; I^2= 0%, p=0.63	-0.7 (-1.1 to -0.4)
	Stair ascent	Controls	Limited	One LR (Gao et al., 2012) study	0.6 (-0.3 to 1.4)
	Stair descent	Controls	Limited	One LR (Gao et al., 2012) study	0.7 (-0.2 to 1.5)
	Running	Contralateral limbs	Limited	One LR (Sato et al., 2013) study	-1.1 (-2.3 to 0)

ES: Effect size; HR: High risk of bias; LR: Low risk of bias;

Table 3.5. Effect sizes for moments between participants with ACLR for between- and within-group comparisons.

Variable	Task	Comparison	Level of evidence	Studies	ES (95%CI)
Flexion moments	Walking	Controls	Strong	Seven LR (Bush-Joseph et al., 2001; Button, Roos, & van Deursen, 2014; Hall et al., 2012; Karimi et al., 2013; Noehren et al., 2013; Webster et al., 2005; Zabala et al., 2013), three HR (Ferber et al., 2002; Lewek et al., 2002; Timoney et al., 1993) studies, I^2=56%, p = 0.02	-0.4 (-0.6 to -0.2)
		Contralateral limbs	Strong	Six LR (Di Stasi et al., 2015; Di Stasi et al., 2013; Hall et al., 2012; Karimi et al., 2013; Roewer et al., 2011; Webster, Feller, et al., 2012; Zabala et al., 2013), three HR (Hooper et al., 2001; Hooper et al., 2002; Timoney et al., 1993) studies; I^2=32%, p=0.13	-0.4 (-0.5 to 0.2)
	Stair ascent	Controls	Strong	Three LR (Bush-Joseph et al., 2001; Hall et al., 2012; Zabala et al., 2013) studies, I^2 =0%, p=0.89	-0.4 (-0.7 to -0.1)
		Contralateral limbs	Strong	Two LR (Hall et al., 2012; Zabala et al., 2013), one HR (Hooper et al., 2002) studies, I^2 =26%, p=0.26	-0.7, (-1.0 to -0.4)
	Stair descent	Controls	Strong	Three LR (Bush-Joseph et al., 2001; Hall et al., 2012; Zabala et al., 2013) studies, I^2 =37%, p=0.20	-0.3 (-0.7 to 0)
		Contralateral limbs	Strong	Two LR (Hall et al., 2012; Zabala et al., 2013); one HR (Hooper et al., 2002) studies, I^2 =43%, p=0.15	-0.5 (-0.8 to -0.1)
	Running	Controls	Limited	One LR (Noehren et al., 2013), one HR (Lewek et al., 2002) studies, I^2=70%, p= 0.07	-0.5 (-0.9 to 0.2)
Adduction moments	Walking	Controls	Strong	Eight LR (Butler et al., 2009; Button et al., 2014; Hall et al., 2012; Karimi et al., 2013; Patterson et al., 2014; Varma et al., 2014; Webster & Feller, 2012b; Zabala et al., 2013) studies, I^2= 81%, p<0.0001	-0.2 (-0.5 to 0)
		Contralateral limbs	Strong	Five LR (Hall et al., 2012; Karimi et al., 2013; Wang et al., 2012; Wang et al., 2013; Webster, Feller, et al., 2012; Zabala et al., 2013), one HR (Hooper et al., 2002) studies; I^2= 0%, p=0.47	-0.3 (-0.6 to -0.1).
	Stair ascent	Controls	Moderate	Two LR (Hall et al., 2012; Zabala et al., 2013), one HR (Hooper et al., 2002) studies; I^2 = 0%, p=0.99	-0.1 (-0.4 to 0.3)
		Contralateral limbs	Strong	Two LR (Hall et al., 2012; Zabala et al., 2013) studies; I^2=64%, p=0.10	-0.4 (-0.7 to 0)
	Stair descent	Controls	Strong	Two LR (Hall et al., 2012; Zabala et al., 2013) studies; I^2 =0%, p=0.71	-0.1 (-0.5 to 0.2)
		Contralateral limbs	Moderate	Two LR (Hall et al., 2012; Zabala et al., 2013), one HR (Hooper et al., 2002) studies; I^2=45%, p=0.14	-0.4 (-0.7 to -0.1)

ES: Effect size; HR: High risk of bias; LR: Low risk of bias;

3.4.5 Joint angles

Peak knee flexion angles during walking were reported in eleven studies (Di Stasi et al., 2013; Ferber et al., 2002; Gao et al., 2012; Georgoulis et al., 2003; Hall et al., 2012; D. Hooper et al., 2001; Lewek et al., 2002; Noehren et al., 2013; Roewer et al., 2011; Webster, Feller, et al., 2012; Webster et al., 2005). The meta-analysis indicated strong evidence for no difference compared to controls (Hall et al., 2012; Lewek et al., 2002) (Ferber et al., 2002; Georgoulis et al., 2003; Noehren et al., 2013; Webster et al., 2005), and strong evidence for less flexion for the ACLR compared to the contralateral limb (ES -0.06 95%CI -0.8 to-0.4) (MD = 4.3°) (Di Stasi et al., 2013; Hall et al., 2012; Hooper et al., 2001; Roewer et al., 2011; Webster, Feller, et al., 2012). A sensitivity test was performed by excluding a study by (Hooper et al., 2001) as this study compared ACLR participants at 2 weeks post-reconstruction with the contralateral limbs. With the exclusion of that study, a significant difference was still evident for peak knee flexion angle between injured and uninjured contralateral limb (ES-0.4, 95%CI -0.60 to-0.12). No significant differences were found for peak knee flexion during stair ascent compared to controls (Figure 3.2, (2.1.3)) and the contralateral limbs (Hall et al., 2012). However, there was moderate evidence that peak flexion was decreased for ACLR knees compared to controls during stair descent (ES-2.69, 95%CI -4.71 to-0.67). (Figure 3.2, (2.1.5)). During running, no significant differences were found for the knee flexion angle compared to controls (Figure 3.2, (2.1.6)).

	ACLR group			Control group				Mean Difference
Study or Subgroup	Mean	SD	Total	Mean	SD	Total	Weight	IV, Fixed, 95% CI
2.1.1 Walking : comparison with control group								
Ferber 2002 (3 months)	19.8	5.35	10	16.13	2.14	10	16.2%	3.67 [0.10, 7.24]
Lewek 2002 (3.3 months)	24.1	3.93	8	26.54	4.87	10	12.5%	-2.44 [-6.51, 1.63]
Georgoulis 2003 (7.5 months)	13.4	9.97	21	14.52	5.81	10	6.7%	-1.12 [-6.70, 4.46]
Webster 2005 (9.3 months)	19.1	4.7	34	21.5	5.6	17	21.6%	-2.40 [-5.50, 0.70]
Noehren 2013 (5 years)	18.5	5	20	20.1	5.1	20	21.1%	-1.60 [-4.73, 1.53]
Hall 2012 (6 years)	1.7	5.3	15	0.4	3	15	21.8%	1.30 [-1.78, 4.38]
Subtotal (95% CI)			**108**			**82**	**100.0%**	**-0.36 [-1.80, 1.08]**
Heterogeneity: Chi² = 9.35, df = 5 (P = 0.10); I² = 47%								
Test for overall effect: Z = 0.49 (P = 0.63)								
2.1.2 Walking: comparison with contralateral limb								
Hooper 2001 (2 weeks)	4.49	3.18	37	13	5	37	35.5%	-8.51 [-10.42, -6.60]
Roewer 2011 (6 months)	23.2	6.6	26	28.1	6.7	26	9.9%	-4.90 [-8.52, -1.28]
Di Stasi 2013 (6 months)	22.5	6.6	42	27.2	6.85	42	15.6%	-4.70 [-7.58, -1.82]
Webster 2012a (10 months)	19.8	5.1	16	20.8	5	16	10.6%	-1.00 [-4.50, 2.50]
Roewer 2011 (2 years)	24.4	7	26	25.4	6.9	26	9.1%	-1.00 [-4.78, 2.78]
Webster 2012a (3.3 years)	20.2	5.4	16	20.1	5.6	16	8.9%	0.10 [-3.71, 3.91]
Hall 2012 (6 years)	1.7	5.3	15	0.9	4.5	15	10.5%	0.80 [-2.72, 4.32]
Subtotal (95% CI)			**178**			**178**	**100.0%**	**-4.34 [-5.48, -3.21]**
Heterogeneity: Chi² = 38.39, df = 6 (P < 0.00001); I² = 84%								
Test for overall effect: Z = 7.48 (P < 0.00001)								
2.1.3 Stair ascent: comparison with control group								
Gao 2012 (3 months)	100	5.6	12	98.6	5.5	12	37.9%	1.40 [-3.04, 5.84]
Hall 2012 (6 years)	60	6.2	15	61.6	3.1	17	62.1%	-1.60 [-5.07, 1.87]
Subtotal (95% CI)			**27**			**29**	**100.0%**	**-0.46 [-3.20, 2.27]**
Heterogeneity: Chi² = 1.09, df = 1 (P = 0.30); I² = 8%								
Test for overall effect: Z = 0.33 (P = 0.74)								
2.1.5 Stair descent: comparison with control group								
Gao 2012 (3 months)	99.2	5.6	12	98	6.5	12	17.2%	1.20 [-3.65, 6.05]
Hall 2012 (6 years)	10.6	3.5	15	14.1	2.8	17	82.8%	-3.50 [-5.72, -1.28]
Subtotal (95% CI)			**27**			**29**	**100.0%**	**-2.69 [-4.71, -0.67]**
Heterogeneity: Chi² = 2.98, df = 1 (P = 0.08); I² = 66%								
Test for overall effect: Z = 2.62 (P = 0.009)								
2.1.6 Running: comparison with control group								
Lewek 2002 (3.3 months)	41.29	4.13	8	46.12	9.18	10	20.5%	-4.83 [-11.20, 1.54]
Noehren 2013 (5 years)	25.7	6.2	20	27.2	4	20	79.5%	-1.50 [-4.73, 1.73]
Subtotal (95% CI)			**28**			**30**	**100.0%**	**-2.18 [-5.07, 0.70]**
Heterogeneity: Chi² = 0.83, df = 1 (P = 0.36); I² = 0%								
Test for overall effect: Z = 1.48 (P = 0.14)								

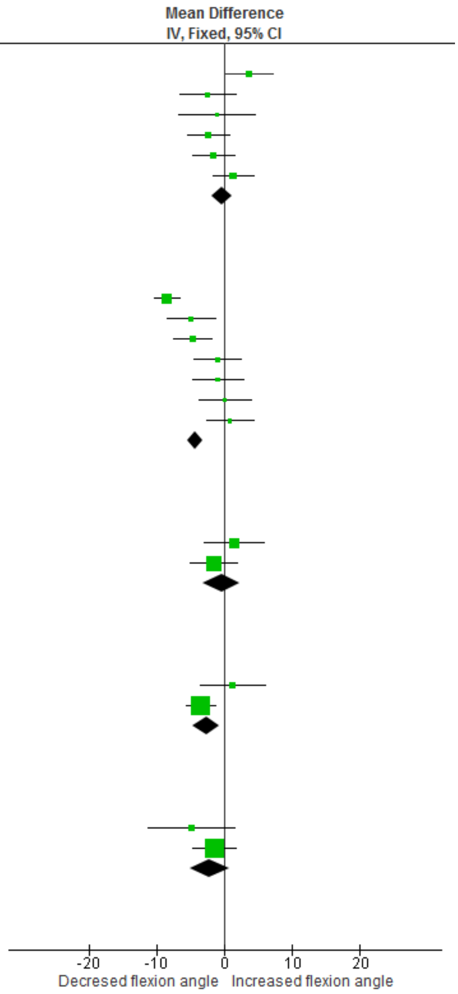


Figure 3.2 Forest plot for peak knee flexion angle during walking, stair navigation and running compared with Control group.

ACLR = anterior cruciate ligament reconstruction; SD = standard deviation; CI = confidence interval; IV = inverse variance.'

Only three studies reported peak *knee adduction angles* (Figure 3.3*)*, with a range from 7.5 months to 5.3 years post-reconstruction (Butler et al., 2009; Georgoulis et al., 2003; Webster & Feller, 2012a). The meta-analysis indicated moderate evidence for no significant difference between the ACLR knee and controls.

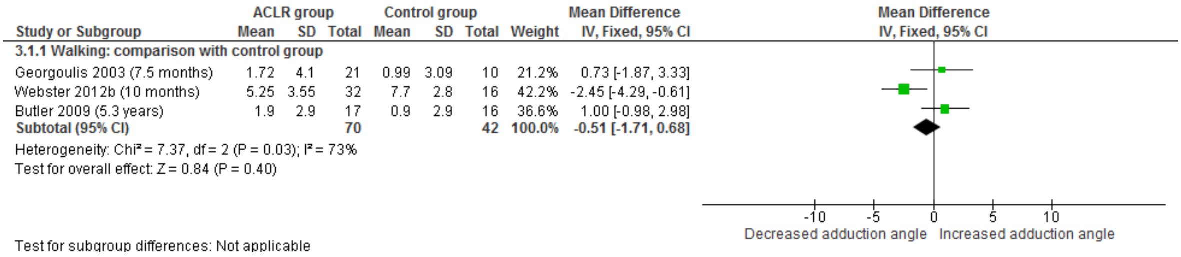


Figure 3.3 Forest plot for peak knee adduction angle during the stance phase of gait during walking compared with Control group.

ACLR = anterior cruciate ligament reconstruction; SD = standard deviation; CI = confidence interval; IV = inverse variance.’

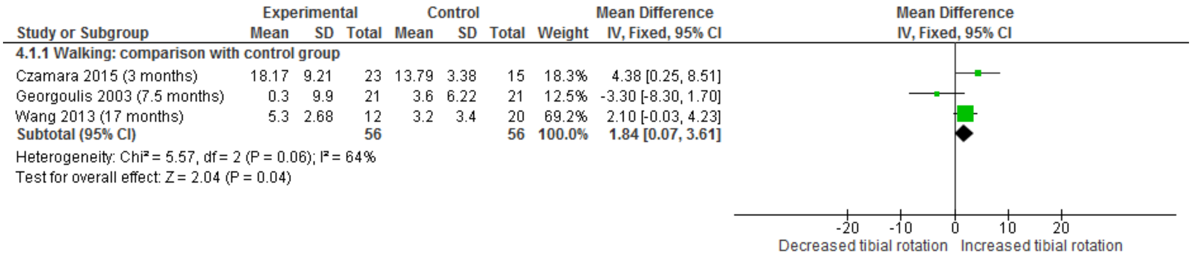


Figure 3.4 Forest plot for peak tibial external rotation angle during the stance phase of gait during walking compared with Control group.

ACLR = anterior cruciate ligament reconstruction; SD = standard deviation; CI = confidence interval; IV = inverse variance.

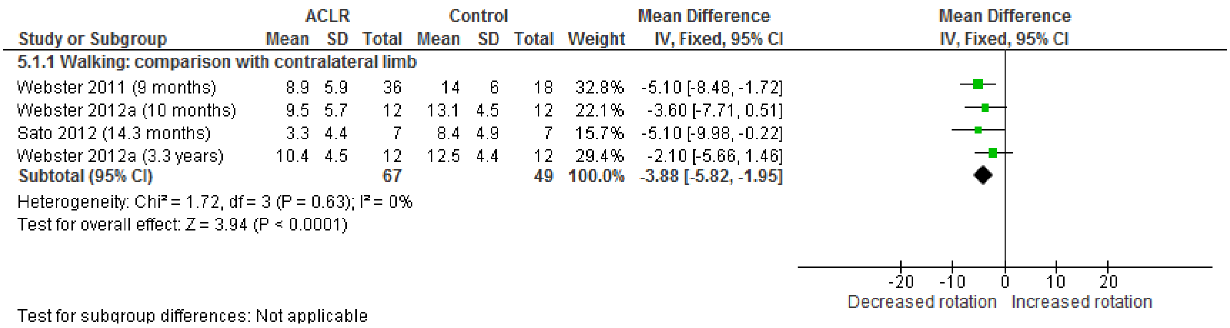


Figure 3.5 Forest plot for peak tibial internal rotation angle during the stance phase of gait compared with Control group.

ACLR = anterior cruciate ligament reconstruction; SD = standard deviation; CI = confidence interval; IV = inverse variance.

In terms of rotation at the knee, studies either reported maximal external or internal tibial rotation during the loading phase (Czamara et al., 2015; Georgoulis et al., 2003; Sato et al., 2013; Webster & Feller, 2011). Strong evidence indicated no significant difference for external tibial rotation for ACLR knees compared to controls during walking (maximum 17 months post-surgery, Figure 3.4). While *peak* external rotation angles were considered for analysis, (Czamara et al., 2015) reported external rotation *at initial foot contact.* Their results were included into the meta-analysis as peak external rotation is most likely to occur at heel strike phase during the stance phase of the walking gait (Lafortune, Cavanagh, Sommer, & Kalenak, 1992). One study (Gao et al., 2012) found less external rotation for the ACLR knees at 3 months post-surgery during stair descent (ES -1.1, 95%CI -2 to -0.2; MD -5.8°, 95%CI -1.8 to -9.9). Strong evidence was found for less tibial internal rotation ES -0.7 (95%CI -1.1 to -0.4) (Figure 3.5) for ACLR knees compared to the contralateral limbs during walking (Sato et al., 2013; Webster & Feller, 2011; Webster, Feller, et al., 2012). However, results of one study (Kuenze et al., 2014) indicated no significant difference between the ACLR and the contralateral limbs while running, with limited evidence (ES -1.1, 95%CI -2.3 to 0).

3.4.6 Joint moments

Overall, participants with ACLR presented with significantly lower *peak flexion moments* during walking compared to controls and the contralateral limbs (strong evidence) (Figure 3.6, (6.2.1 and 6.2.2)). Strong evidence was found for peak flexion moments being lower for the injured side compared to the contralateral uninjured sides during walking, stair ascent and descent after ACLR (Figure 3.6, (6.2.3 to 6.2.6)). Moderate evidence indicated no significant differences during running in ACLR participants compared to controls (Figure 3.6, (6.2.7)).

	ACLR group			Control				Std. Mean Difference
Study or Subgroup	**Mean**	**SD**	**Total**	**Mean**	**SD**	**Total**	**Weight**	**IV, Fixed, 95% CI**
6.2.1 Walking : comparison with control group								
Ferber 2002 (3 months)	0.1	0.05	10	0.08	0.12	10	5.7%	0.21 [-0.67, 1.09]
Lewek 2002 (3.3 months)	0.41	0.33	8	0.71	0.26	10	4.4%	-0.98 [-1.97, 0.02]
Karimi 2013 (6 months)	0.46	0.46	15	0.61	0.5	15	8.4%	-0.30 [-1.02, 0.42]
Timoney 1993 (9 months)	2.02	1.14	10	3.74	0.82	10	4.0%	-1.66 [-2.71, -0.61]
Webster 2005 (9.3 months)	2.2	1.16	17	2.8	1	17	9.3%	-0.54 [-1.23, 0.15]
Button 2014 (13.5 months)	0.035	0.017	21	0.034	0.017	21	11.9%	0.06 [-0.55, 0.66]
Bush 2001 (22 months)	2	1.2	22	2.3	1.3	22	12.4%	-0.24 [-0.83, 0.36]
Zabala 2013 (26 months)	2.23	1.29	45	2.59	1.17	45	25.3%	-0.29 [-0.71, 0.13]
Noehren 2013 (5 years)	0.04	0.2	20	0.23	0.1	20	9.5%	-1.18 [-1.85, -0.50]
Hall 2012 (6 years)	0.42	0.21	15	0.45	0.14	17	9.0%	-0.17 [-0.86, 0.53]
Subtotal (95% CI)			**183**			**187**	**100.0%**	**-0.40 [-0.61, -0.19]**
Heterogeneity: Chi² = 17.17, df = 9 (P = 0.05); I² = 48%								
Test for overall effect: Z = 3.71 (P = 0.0002)								
6.2.2 Walking : comparison with contralateral limb								
Hooper 2001 (2 weeks)	0.3	0.13	8	0.35	0.12	8	2.9%	-0.38 [-1.37, 0.61]
Hooper 2002 (6 months)	0.3	0.13	8	0.35	0.12	8	2.9%	-0.38 [-1.37, 0.61]
Karimi 2013 (6 months)	0.46	0.46	15	0.45	0.35	15	5.6%	0.02 [-0.69, 0.74]
Roewer 2011 (6 months)	0.4	0.58	26	0.5	0.65	26	9.8%	-0.16 [-0.70, 0.38]
Di Stasi 2013 (6 months)	0.39	0.15	42	0.51	0.13	42	14.5%	-0.85 [-1.29, -0.40]
Timoney 1993 (9 months)	2.02	1.14	10	3.1	1.35	10	3.4%	-0.83 [-1.75, 0.09]
Di Stasi 2015 (6 months)	0.38	0.11	39	0.48	0.11	39	13.3%	-0.90 [-1.37, -0.43]
Webster 2012a (10 months)	0.39	0.24	16	0.43	0.26	16	6.0%	-0.16 [-0.85, 0.54]
Hooper 2002 (12 months)	0.31	0.16	9	0.38	0.12	9	3.3%	-0.47 [-1.41, 0.47]
Roewer 2011 (2 years)	0.5	0.91	26	0.55	0.92	26	9.8%	-0.05 [-0.60, 0.49]
Zabala 2013 (26 months)	2.23	1.29	45	2.16	1.17	45	16.9%	0.06 [-0.36, 0.47]
Webster 2012a (3.3 years)	0.41	0.23	16	0.46	0.25	16	6.0%	-0.20 [-0.90, 0.49]
Hall 2012 (6 years)	0.42	0.21	15	0.5	0.31	15	5.6%	-0.29 [-1.01, 0.43]
Subtotal (95% CI)			**275**			**275**	**100.0%**	**-0.36 [-0.53, -0.19]**
Heterogeneity: Chi² = 18.04, df = 12 (P = 0.11); I² = 33%								
Test for overall effect: Z = 4.10 (P < 0.0001)								
6.2.3 Stair ascent : comparison with control group								
Bush 2001 (22 months)	5.3	1.8	22	6.1	2.1	22	26.6%	-0.40 [-1.00, 0.20]
Zabala 2013 (26 months)	6.05	1.54	45	6.58	1.07	45	54.6%	-0.40 [-0.81, 0.02]
Hall 2012 (6 years)	1.05	0.21	15	1.22	0.33	17	18.8%	-0.59 [-1.30, 0.12]
Subtotal (95% CI)			**82**			**84**	**100.0%**	**-0.43 [-0.74, -0.13]**
Heterogeneity: Chi² = 0.23, df = 2 (P = 0.89); I² = 0%								
Test for overall effect: Z = 2.76 (P = 0.006)								
6.2.4 Stair ascent: comparison with contralateral limb								
Hooper 2002 (6 months)	0.52	0.14	8	0.75	0.21	8	9.1%	-1.22 [-2.31, -0.12]
Zabala 2013 (26 months)	6.05	1.54	45	7.01	0.85	45	59.0%	-0.77 [-1.19, -0.34]
Hooper 2002 (12 months)	0.57	0.13	9	0.71	0.13	9	10.9%	-1.03 [-2.02, -0.03]
Hall 2012 (6 years)	1.05	0.21	15	1.07	0.18	15	21.1%	-0.10 [-0.82, 0.62]
Subtotal (95% CI)			**77**			**77**	**100.0%**	**-0.69 [-1.02, -0.36]**
Heterogeneity: Chi² = 4.06, df = 3 (P = 0.26); I² = 26%								
Test for overall effect: Z = 4.13 (P < 0.0001)								
6.2.5 Stair descent: comparison with control group								
Bush 2001 (22 months)	5.2	2.2	22	6	1.3	22	26.5%	-0.43 [-1.03, 0.16]
Zabala 2013 (26 months)	3.85	1.68	45	4	1.85	45	55.5%	-0.08 [-0.50, 0.33]
Hall 2012 (6 years)	1.04	0.24	15	1.26	0.28	17	18.0%	-0.82 [-1.54, -0.09]
Subtotal (95% CI)			**82**			**84**	**100.0%**	**-0.31 [-0.62, -0.00]**
Heterogeneity: Chi² = 3.19, df = 2 (P = 0.20); I² = 37%								
Test for overall effect: Z = 1.97 (P = 0.05)								
6.2.6 Stair descent: comparison with contralateral limb								
Hooper 2002 (6 months)	0.47	0.11	8	0.65	0.11	8	7.8%	-1.55 [-2.71, -0.39]
Hooper 2002 (12 months)	0.59	0.13	9	0.68	0.11	9	11.4%	-0.71 [-1.67, 0.25]
Zabala 2013 (26 months)	3.85	1.85	45	4.64	1.76	45	60.2%	-0.43 [-0.85, -0.02]
Hall 2012 (6 years)	1.04	0.24	15	1.04	0.21	15	20.6%	0.00 [-0.72, 0.72]
Subtotal (95% CI)			**77**			**77**	**100.0%**	**-0.46 [-0.79, -0.14]**
Heterogeneity: Chi² = 5.25, df = 3 (P = 0.15); I² = 43%								
Test for overall effect: Z = 2.80 (P = 0.005)								
6.2.7 Running: comparison with control group								
Lewek 2002 (3.3 months)	1.82	0.64	8	2.34	0.67	10	29.0%	-0.75 [-1.72, 0.22]
Noehren 2013 (5 years)	0.07	0.4	20	0.11	0.1	20	71.0%	-0.13 [-0.76, 0.49]
Subtotal (95% CI)			**28**			**30**	**100.0%**	**-0.31 [-0.84, 0.21]**
Heterogeneity: Chi² = 1.11, df = 1 (P = 0.29); I² = 10%								
Test for overall effect: Z = 1.18 (P = 0.24)								

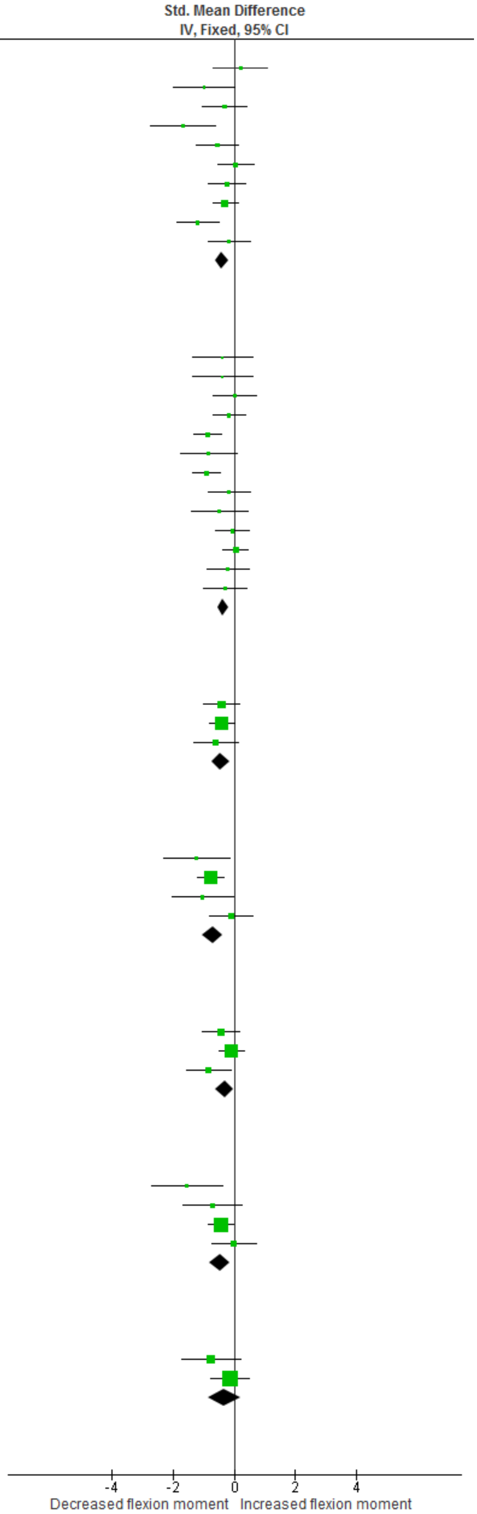


Figure 3.6 Forest plot for knee flexion moment during stance phase of gait in different activities.

ACLR = anterior cruciate ligament reconstruction; SD = standard deviation; CI = confidence interval; IV = inverse variance

The meta-analysis showed moderate to strong evidence for significantly lower first p*eak adduction moments* during walking for the ACLR knees when compared to controls and to the contralateral limbs respectively (Figure 3.7, (7.1.1 and 7.1.2)). Strong and moderate evidence indicated no significant differences to be present for the peak adduction moments during stair ascent and descent respectively for the ACLR knees compared to the Control group (Figure. 3.7, (7.1.3 and 7.1.5)). In contrast, lower peak adduction moments were found for ACLR during stair ascent (moderate evidence) and descent (strong evidence) compared to the contralateral limbs (Figure 3.7, (7.1.4 and 7.1.6)). No studies evaluating adduction moments during running were identified and included in the review.

Study or Subgroup	ACLR Mean	ACLR SD	ACLR Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Fixed, 95% CI
7.1.1 Walking: comparison with control group								
Karimi 2013 (6 months)	0.51	0.27	15	0.35	0.12	15	10.1%	0.75 [0.00, 1.49]
Webster 2012 (10.3 months)	0.28	0.07	32	0.4	0.08	16	11.8%	-1.61 [-2.30, -0.92]
Button 2013 (13.5 months)	0.034	0.013	21	0.037	0.01	21	15.1%	-0.25 [-0.86, 0.35]
Zabala 2013 (26 months)	2.67	0.64	45	2.94	0.73	45	32.1%	-0.39 [-0.81, 0.03]
Patterson 2014 (3.5 years)	0.31	0.08	17	0.41	0.12	17	10.9%	-0.96 [-1.67, -0.24]
Varma 2014 (4.5 years)	0.23	0.16	12	0.2	0.13	12	8.7%	0.20 [-0.60, 1.00]
Butler 2009 (5.3 years)	0.36	0.08	17	0.3	0.09	16	11.2%	0.69 [-0.02, 1.39]
Subtotal (95% CI)			**159**			**142**	**100.0%**	**-0.29 [-0.52, -0.05]**
Heterogeneity: Chi² = 33.96, df = 6 (P < 0.00001); I² = 82%								
Test for overall effect: Z = 2.39 (P = 0.02)								
7.1.2 Walking: comparison with contralateral limb								
Karimi 2013 (6 months)	0.51	0.27	15	0.42	0.15	15		Not estimable
Hooper 2002 (6 months)	0.16	0.04	8	0.15	0.05	8	6.4%	0.21 [-0.77, 1.19]
Webster 2012a (10 months)	0.52	0.12	16	0.58	0.14	16	12.5%	-0.45 [-1.15, 0.25]
Hooper 2002 (12 months)	0.19	0.04	9	0.18	0.05	9	7.2%	0.21 [-0.72, 1.14]
Wang 2012 (14 months)	0.35	0.16	19	0.46	0.15	19	14.3%	-0.69 [-1.35, -0.04]
Zabala 2013 (26 months)	2.67	0.64	45	2.95	0.57	45	35.1%	-0.46 [-0.88, -0.04]
Webster 2012a (3.3 years)	0.56	0.15	16	0.63	0.19	16	12.6%	-0.40 [-1.10, 0.30]
Hall 2012 (6 years)	0.5	0.13	15	0.48	0.2	15	12.0%	0.12 [-0.60, 0.83]
Subtotal (95% CI)			**128**			**128**	**100.0%**	**-0.32 [-0.57, -0.08]**
Heterogeneity: Chi² = 5.63, df = 6 (P = 0.47); I² = 0%								
Test for overall effect: Z = 2.56 (P = 0.01)								
7.1.3 Stair ascent: comparson with control group								
Hooper 2002 (6 months)	0.18	0.06	8	0.19	0.13	8	8.5%	-0.09 [-1.07, 0.89]
Hooper 2002 (12 months)	0.21	0.08	9	0.23	0.11	9	9.6%	-0.20 [-1.12, 0.73]
Zabala 2013 (26 months)	2.67	0.64	45	2.68	0.86	45	48.1%	-0.01 [-0.43, 0.40]
Hall 2012 (6 years)	0.51	0.17	15	0.52	0.11	17	17.0%	-0.07 [-0.76, 0.63]
Hall 2012 (6 years)	0.5	0.13	15	0.46	0.09	17	16.7%	0.35 [-0.35, 1.05]
Subtotal (95% CI)			**92**			**96**	**100.0%**	**0.01 [-0.27, 0.30]**
Heterogeneity: Chi² = 1.22, df = 4 (P = 0.88); I² = 0%								
Test for overall effect: Z = 0.10 (P = 0.92)								
7.1.4 Stair ascent: comparison with contralateral limb								
Zabala 2013 (26 months)	2.67	0.64	45	3.09	0.88	45	74.4%	-0.54 [-0.96, -0.12]
Hall 2012 (6 years)	0.51	0.17	15	0.48	0.19	15	25.6%	0.16 [-0.56, 0.88]
Subtotal (95% CI)			**60**			**60**	**100.0%**	**-0.36 [-0.72, 0.00]**
Heterogeneity: Chi² = 2.75, df = 1 (P = 0.10); I² = 64%								
Test for overall effect: Z = 1.95 (P = 0.05)								
7.1.5 Stair descent: comparison with control group								
Zabala 2013 (26 months)	2.72	0.9	45	2.86	0.91	45	73.8%	-0.15 [-0.57, 0.26]
Hall 2012 (6 years)	0.19	0.14	15	0.19	0.1	17	26.2%	0.00 [-0.69, 0.69]
Subtotal (95% CI)			**60**			**62**	**100.0%**	**-0.11 [-0.47, 0.24]**
Heterogeneity: Chi² = 0.14, df = 1 (P = 0.71); I² = 0%								
Test for overall effect: Z = 0.62 (P = 0.53)								
7.1.6 Stair descent: comparison with contralateral limb								
Hooper 2002 (6 months)	0.18	0.09	8	0.23	0.08	8	10.3%	-0.56 [-1.56, 0.45]
Hooper 2002 (12 months)	0.29	0.13	9	0.24	0.05	9	11.7%	0.48 [-0.46, 1.42]
Zabala 2013 (26 months)	2.72	0.9	45	3.3	0.91	45	57.7%	-0.64 [-1.06, -0.21]
Hall 2012 (6 years)	0.19	0.14	15	0.2	0.11	15	20.2%	-0.08 [-0.79, 0.64]
Subtotal (95% CI)			**77**			**77**	**100.0%**	**-0.38 [-0.71, -0.06]**
Heterogeneity: Chi² = 5.43, df = 3 (P = 0.14); I² = 45%								
Test for overall effect: Z = 2.33 (P = 0.02)								
Test for subgroup differences: Chi² = 5.28, df = 5 (P = 0.38), I² = 5.3%								

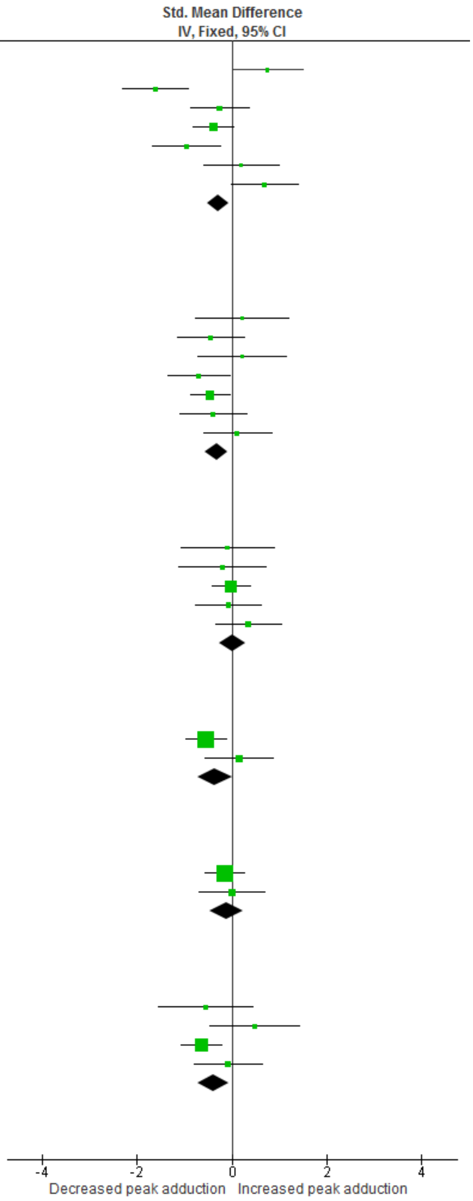


Figure 3.7 Forest plot for the first peak of knee adduction moment during the stance phase of gait in different activities.

ACLR = anterior cruciate ligament reconstruction; SD = standard deviation; CI = confidence interval; IV = inverse variance;

ES for differences for the flexion and adduction moments were low (< 0.59) for all comparisons, except for the comparison of flexion moments during stair ascent (ES 0.7, 95%CI 0.1 to 0.4) and descent (ES 0.5, 95% CI 0.1 to 0.8), when comparing ACLR knees to the contralateral limbs.

3.4.7 Time course of recovery

The qualitative assessment of the forest plots suggests patients tend to restore peak knee flexion angle over time after surgery for studies that included participants up to 6 years, and present peak knee flexion angle that is similar to the contralateral limb (Figure 3.2). Such an improvement over time, however, was not evident for peak flexion moments during walking. When ascending and descending stairs, patients tended to present improved flexion moments over time when compared to the contralateral sides, but not when compared to controls (Figure 3.6).

During walking, peak adduction moments appeared to be significantly lower in participants with ACLR than controls within the first year following surgery (average 10.3 months) (Webster & Feller, 2012b). However, while not significant (95%CI, -0.02 to 1.4), these adduction moments showed a tendency to be slightly higher than controls at a later phase (5.3 years) (Butler et al., 2009) (Figure 3.7). Interestingly, (Karimi et al., 2013) found higher peak adduction moments at 6 months post-reconstruction compared to controls. Functional braces were worn by their participants for 3 months post-surgery, which were not reported to be worn in any of the other studies. A sensitivity test was performed by excluding the adduction moments for this study (Karimi et al., 2013), and the results indicate that, overall, peak adduction moments were significantly lower in ACLR group compared to Control group (ES -0.32, 95%CI -0.55 to -0.08). When excluding their results, there appears to be a response in time, from lower to equivalent adduction moments for the ACLR group compared to controls while walking.

3.5 Discussion

The primary aim of this review was to compare knee joint angles and moments in participants with ACLR to the contralateral limbs and to age-matched controls during walking, stair climbing and running. In terms of joint angles, moderate to strong evidence was found for no differences for peak flexion during walking, stair ascent and jogging when comparing the ACLR knees to controls. However, when compared to the uninjured contralateral sides, less flexion and less internal rotation were found for the ACLR knees during walking. During stair descent, peak flexion was decreased for ACLR knees compared to controls. There was moderate evidence for no differences for peak adduction angles between the ACLR knee and controls. Moderate to strong evidence was found for lower peak flexion moments in participants with ACLR during walking and stair ascent compared to controls and to the contralateral limbs. Moderate to strong evidence also indicated lower peak adduction moment for the ACL-reconstructed knees during walking, stair ascent, and descent compared to the contralateral limbs, and during walking when compared to the controls.

3.5.1 Peak joint angles

Results of the meta-analysis suggest that participants with ACLR regain similar peak knee flexion angles compared to the Control group during walking by 6 years following surgery (Figure 3.2). However, pooled peak flexion angles were lower in the ACLR knee compared to the contralateral sides (ES 0.6, 95%CI -0.4 to -0.8). The MD 4.3° was higher than the minimal clinically important difference of 3° reported for knee flexion during the stance phase of walking (Di Stasi & Snyder-Mackler, 2012). This difference was influenced in part by the findings by (Hooper et al., 2001) at 2 weeks post-surgery: the MD 8.5° which may be due to pain or swelling at early stages after surgery. Considering the individual studies, limb asymmetry for peak flexion angles was evident until 6 months post-reconstruction (Roewer et al., 2011; Di Stasi et al., 2013), while no significant bilateral differences were found, on average, 10 months to 6 years following surgery.

Similarly, our meta-analysis indicated no significant between-group differences for knee adduction and external rotation angles during walking. However, peak external rotation was decreased during stair descent based on one study (Gao et al., 2012). Internal rotation was decreased during walking for the ACLR knee compared to contralateral limb. Rotational shifts varied from 1 to 5.8°. A biomechanical model of degeneration showed that 5° rotational shift may be enough to cause accelerated degeneration of the cartilage (Andriacchi & Mündermann, 2006) due to alterations in the stresses applied to joint surfaces (Tashman, Collon, Anderson, Kolowich, & Anderst, 2004). Whether these small differences in kinematics for participants with ACLR compared to controls and contralateral limbs indicate increased risk for post-traumatic knee osteoarthritis still needs confirmation.

3.5.2 Joint moments

Strong evidence was found that peak flexion moments were significantly lower in participants with ACLR during walking, stair ascent and descent activities compared to controls and contralateral limb. However, the effect size were small during walking and when compared to the controls during stair ascent and descent, while moderate effect sizes were found for decreased flexion moments when compared to the contralateral sides during stair ascent and descent. It is thus possible that an asymmetry may be more evident during stair ascent and descent than during walking. Peak external flexion moments are considered to reflect net quadriceps function (Andriacchi & Dyrby, 2005) and reduced moments may be associated with lower quadriceps strength (Schmitt et al., 2015). Neurophysiological changes following ACL injury and reconstruction have been shown to include decreased lower limb muscle activation, as determined by electromyography on the injured side (Nyland et al., 2010) and lower cortical activation in injured limbs compared to uninjured and healthy population, contributing towards reduced net quadriceps function (Kuenze et al., 2015). The presence of pain reported even after 2-5 years of surgery (Kartus et al., 1999), or reflex inhibition (Hodges & Tucker, 2011) could further influence the movement patterns, as apparent with reduced flexion moments. Furthermore, compensatory movements at the hip and trunk may also decrease knee joint loading (Courtney & Rine, 2006). It is thus likely that multiple mechanisms contribute towards long-term decreased flexion moments in the ACLR knees.

Similar to external knee flexion moments, the adduction moments for the ACLR knees were significantly smaller during walking when compared to controls, albeit with low effect size. No significant differences were found for both the flexion moments and adduction moments during stair descent for the ACLR knees compared to the controls, while they were lower for the ACLR knees compared to the contralateral side. This indicates a bilateral asymmetry during this task and could infer that during stair descent, the contralateral side has higher flexion and adduction moments than controls. While this is speculative, compensatory patterns may be evident on the contralateral side (Hart et al., 2010) which are likely due to central nervous system changes following the injury and surgery. Such changes have been documented in patients with ACL-deficient knees (Courtney & Rine, 2006).

The meta-analysis along with sensitivity test for one study (Karimi et al., 2013) showed peak adduction moments were lower compared to controls in participants with ACLR the short- and medium-term (up to 3.5 years) and higher as time following reconstruction progresses. Our findings contrast thus with those by (Hart, Culvenor, et al., 2015) who recently found that the frontal plane moments may not be affected by ACLR. Our findings, thus, suggest that frontal plane moments cannot yet be disregarded as outcomes and long-term consequences of ACLR. The finding of lower adduction moments in the ACLR knees contrast with increased adduction moments often reported in patients with knee osteoarthritis (Setton, Elliott, & Mow, 1999). Risk of progression of osteoarthritis in patients with that disorder increases 6.46 times with 1% increase in adduction moments (Miyazaki et al., 2002), hence the magnitude of adduction moments is correlated with osteoarthritis severity (Foroughi et al., 2009; Sharma et al., 1998). While decreased adduction moments in the early phase following ACLR may reflect decreased weight-bearing and compensatory strategies of the trunk, hip and ankle (Myer, Chu, Brent, & Hewett, 2008; Paterno, Ford, Myer, Heyl, & Hewett, 2007; Setton et al., 1999), a combination of changing flexion and adduction moments and joint rotations may contribute towards loading at unconditioned areas of the cartilage potentially leading to development of osteoarthritis (Andriacchi, Briant, Bevill, & Koo, 2006). Studies included in the present review did not report radiographic osteoarthritis changes for their participants, thus it is unknown whether those with higher adduction moments present with radiographic signs of osteoarthritis (Miyazaki et al., 2002). Whether changes for external adduction moments during functional tasks predict the onset of osteoarthritis following ACLR still needs to be substantiated. While the development of osteoarthritis is multi-factorial, these biomechanical factors should be explored longitudinally in all planes.

3.5.3 Clinical implications

Overall, reduced flexion and adduction moments indicate altered joint loading in the long-term following ACLR. These changes are likely associated with quadriceps weakness (Shelburne, Torry, & Pandy, 2006) and various neurophysiological mechanisms (Barret, 1991; Urbach, Nebelung, Becker, & Awiszus, 2001; Urbach, Nebelung, Röpke, Becker, & Awiszus, 2000), and are potentially associated with risk of early onset joint degeneration (Roos, Adalberth, Dahlberg, & Lohmander, 1995; Roos, Neu, Hull, & Howell, 2005), due to suboptimal joint loading during functional tasks such as walking, running, stair navigation (Knoll, Kiss, & Kocsis, 2004). Altered kinematics along with reduced flexion moments may significantly change the stress distribution within the cartilage and initiates a degenerative process (Setton et al., 1999). Di Stasi et al., 2013 showed that athletes with a superior functional performance at 6 months following ACLR appear to demonstrate less asymmetrical gait patterns compared to those that did not pass functional return to play criteria. It thus appears to be important to include assessment of potential gait asymmetries following ACLR in decision making for readiness for rehabilitation progression and return to sports (Di Stasi et al., 2013; Myer et al., 2008). While small differences in walking may not be detectable on clinical examination, these may be more evident during high knee loading activities, such as stair ascent/descent and, running (Myer et al., 2008) and jumping (Paterno et al., 2007). The finding of movement and loading asymmetries in the current review indicates that it may be important for people with ACRL to continue with exercise programme focusing on strength, neuromuscular control and proprioception even after rehabilitation period is completed.

3.5.4 Methodological considerations and directions for future research

The risk of bias assessment identified methodological limitations for the included studies: the absence of outcome measurer blinding, reporting reliability of methodology, lack of confounding factors as control of gait speed, a priori power calculation for sample size. While blinding of the researcher is difficult during data collection due to visible scarring at the operated knee, blinding for the participant group (Control versus ACLR) can occur while processing kinematic and kinetic data.

Sixteen studies included in the meta-analysis controlled the speed of the tasks (Bush-Joseph et al., 2001; Butler et al., 2009; K. Button et al., 2014; Di Stasi et al., 2015; Di Stasi et al., 2013; Ferber et al., 2002; Georgoulis et al., 2003; Kuenze et al., 2014; Lewek et al., 2002; Noehren et al., 2013; Roewer et al., 2011; Timoney et al., 1993; Varma et al., 2014; Wang et al., 2013; Webster & Feller, 2012a; Webster et al., 2005). A compensatory strategy to maintain or decrease joint loading is to walk slower (Robbins & Maly, 2009). Thus, in those studies where speed was not reported, it is possible that participants with ACLR may have walked slower thereby maintaining or controlling the joint loading effectively. This could lead to no significant differences between-group, as seen for stair descent for flexion and adduction moments. Furthermore, other compensatory strategies which develop over time post-reconstruction, such as transferring the load to the hip and ankle (Orishimo, Kremenic, Mullaney, McHugh, & Nicholas, 2010) and compensation with trunk lean, can also be used to decrease joint moments, as shown in patients with knee osteoarthritis (Annegret Mündermann, Dyrby, & Andriacchi, 2005; Simic, Hinman, Wrigley, Bennell, & Hunt, 2011). These factors should be addressed in future research.

Only cross-sectional studies or baseline measures of RCTs were considered for the purpose of the time course of recovery analysis in this review. However, longitudinal studies following patients at different time points following ACLR are needed to fully investigate how gait biomechanics change over time, and how these changes may influence the development of osteoarthritis or re-injury. Furthermore, the aim of this review was to explore differences for peak knee joint angles and moments when comparing people with ACLR to controls, and not between different surgical or rehabilitative programs. Findings of groups of participants with ACLR undergoing different procedures within individual studies were thus combined into grand means for the meta-analyses, which masks differences between these groups. Findings of this review are thus limited to comparisons with controls and when comparing the ACLR knees to the contralateral uninjured sides, irrespective of surgical methods. Finally, this review was limited to the discrete variables of peak angles and moments, and did not explore biomechanical variables in other phases of the gait cycle.

3.6 **Conclusion**

Joint kinematics of ACL reconstructed knees were found to be similar to Control groups during walking and stair navigation within a few months after surgery. However, differences in knee external moments persist over a longer period. The meta-analysis indicated lower pooled external flexion moments for people with ACLR compared to controls during walking and stair ascent. The meta-analysis also indicated decreased peak adduction moments during walking and stair navigation for ACLR-knees, specifically when compared to contralateral limbs. Based on individual studies included in the review, such moments may be lower compared to controls in the early phase following ACLR (10 months), but higher at later phase (5 years) after surgery. While this review did not explore compensatory mechanisms, it is likely that multiple mechanisms influence altered gait patterns, including changes in muscle function and neuromuscular control at the trunk, hip knee, and ankle. Gait patterns at the knee are not fully restored after more than 5 years following surgery. It may also indicate that early programs post-surgery are undertaken poorly and hence they should be re-examined. Also, it indicates that long-term rehabilitative or maintenance programmes may need to be considered for patients undergoing ACLR.

3.7 **Summary**

This chapter highlighted the partial recovery of knee flexion and adduction moments following ACLR during stair ascent and descent. The included studies in this review explored the moments up to an average of 5 years following surgery, however, there is need to explore the moments in the long-term as it may be possible that moments have higher magnitude as the time since surgery increases. Therefore, moments were measured and analysed in participants with ACLR from 2 to 10 years following surgery and compared with the contralateral limb and the Control group (Chapter 6).

The next Chapter (Chapter 4) is a cross-sectional study aimed to explore and compare the patient-reported outcomes, muscle strength, physical performance and knee laxity related outcomes in participants with ACLR with the Control group

4 Patient-reported outcomes and physical performance measures in participants with ACLR compared to a Control group – a cross-sectional study

4.1 Prelude to Chapter 4

Participants with ACL injury and surgery are at higher risk of early onset of osteoarthritis, which may take a few years for development. Following the patient-centered approach, it is important to explore patient-reported outcomes. The literature review (Chapter 2) indicated that the muscle strength and physical performance deficits on the injured side in participants with ACLR may persist in the long term post-surgery. This indicated the need to explore the physical constraints related to the knee in participants with ACLR in the context of New Zealand.

In this study, patient-reported outcomes, muscle strength, physical performance and knee laxity in participants with ACLR were measured and compared with their contralateral limb, and to an uninjured Control group. This chapter provides a detailed description of the entire participant cohort involved in this thesis before exploring the biomechanics-related outcomes in participants 2 to 10 years following surgery (Chapter 6).

4.2 Background

Anterior cruciate ligament reconstruction surgery is undertaken to restore joint anatomy, but the joint function is more than just the restoration of anatomical structures. Assessment of joint function requires muscle strength assessment. Strength deficits can persist until 5 years post-surgery on the injured side in the knee extensor group compared to the Control group (Keays, Bullock-Saxton, Keays, Newcombe, & Bullock, 2007; Wolf Petersen, Pouria Taheri, Phillip Forkel, & Thore Zantop, 2014) and were related to the presence of osteoarthritis in participants with ACLR (Keays et al., 2007). Muscle strength deficits have been reported to persist from 3 years (Hiemstra, Webber, MacDonald, & Kriellaars, 2007) to 7 years following surgery (Yasuda, Ohkoshi, Tanabe, & Kaneda, 1991). Strength deficits, particularly quadriceps strength asymmetry following ACLR, is known to alter knee joint biomechanics at time of return to activity (Palmieri-Smith & Lepley, 2015). Patients with low quadriceps strength displayed greater movement asymmetries at the knee in the sagittal plane such that there was greater symmetry for knee flexion angle and external moments in patients with high and moderate quadriceps symmetry compared to those with low symmetry during single leg hop (Palmieri-Smith & Lepley, 2015). Also, quadriceps strength was related to movement asymmetries and physical performance (Palmieri-Smith & Lepley, 2015). It is important to explore the muscle strength deficits in the current thesis as the results can help to understand the knee biomechanics clearly. Presence of muscle strength deficits are more likely to be found during the maximal muscle force output, therefore, peak torque during maximal muscle force output was used as an outcome measure. Further, eccentric quadriceps muscle activity is required during jumping, landing and stair descent (Bobbert, 2001), while concentric quadriceps and hamstring strength is required during the stair navigation activity (Benedetti, Agostini, Knaflitz, & Bonato, 2012). Assessing both concentric and eccentric muscle strength thus is important to understand function related to daily activities.

Considering patients’ perspectives is also needed to fully understand the influence of injury on joint-related and general quality of life. A review has reported good scores in patient-reported outcomes up to 10 years following ACLR (Magnussen et al., 2015); however, the quality of life for participants with ACLR can deteriorate in the long-term following surgery (Tengman, 2014). Muscle function was associated with future patient-reported outcomes in young adults with ACL injury suggesting that improving muscle function during rehabilitation could improve present and future patient–reported outcomes (Flosadottir, Roos, & Ageberg, 2016). It has been reported that patients experience decreased levels of physical activity up to several years after surgery (Magnussen et al., 2011), which may be related to the performance levels on the injured side. Exploring the physical performance on the injured side can provide information relating to the neuromuscular status of the limb.

Along with the muscles providing the dynamic stability, knee stability is also determined by joint laxity. Conflicting research reports exist in the literature regarding antero-posterior knee laxity following surgery, with some studies reporting a decrease in knee laxity (Ahldén et al., 2009), while others reported no change up to 7 years following surgery (Semay et al., 2016). Decrease in the laxity of the knee may be related to development of stiffness of the knee in the long-term. However, less is known about knee laxity in participants with ACLR in the long-term.

4.2.1 Aim of the study

The aim of this study was to determine the patient-reported outcomes, thigh muscle strength, and physical performance and knee laxity-related outcomes of participants with ACLR, and to compare them with the contralateral limb and with the Control group.

4.2.2 Hypothesis

- Participants with ACLR will have lower scores on the KOOS, SF-12 Health survey, Confidence during Sports, and Tegner scores compared with the Control group.
- Participants with ACLR will have lower isokinetic concentric and eccentric peak torque of the quadriceps, and concentric peak torque of the hamstrings, compared to the contralateral limb and the Control group.
- Participants with ACLR will demonstrate lower performance during the single-leg hop compared to the contralateral limb and the Control group.
- Participants with ACLR will have reduced knee laxity in the sagittal plane on the injured side compared to the contralateral limb, and compared to the Control group.

4.3 Methods

The STROBE (Strengthening the Reporting of Observational studies in Epidemiology) statement was used for reporting this study (Von Elm et al., 2014).

4.3.1 Study design

This was a cross-sectional study, assessing the within- and between-group differences among the ACLR and Control group.

4.3.2 Ethical approval

The University of Otago Human Ethics Committee granted approval for the study (reference number H15/034) (Appendix-B1 to B3). Consultation with the Ngāi Tahu Research Consultation Committee (Māori committee) was completed prior to the study (Appendix-B4).

4.3.3 Study settings

The study was carried out at the Mark Steptoe Laboratories located in the Centre for Health, Activity and Rehabilitation Research (CHARR), School of Physiotherapy at the University of Otago, Dunedin, New Zealand.

4.3.4 Recruitment of participants with the ACLR and the Control group

Participants were recruited from the Otago region of the South Island of New Zealand via adverts or leaflets sent to local community newspapers (Appendix B5), sports clubs, swimming pools, fitness centres, and posted on public notice boards (Appendix B6). Physiotherapy and sports physicians likely to be working with sports people with past ACL injury and reconstructions were sent information sheets and leaflets, and asked to provide information about the study to their patients. Leaflets were placed in physiotherapy and general practice patient waiting areas. Study information was also sent to Sports Physiotherapy New Zealand, and an advert was placed in their monthly newsletter to members. Information was posted on the School of Physiotherapy website and the School of Physiotherapy Clinics' Facebook site. Participants for the Control group were recruited by the same community adverts, in addition to word-of-mouth during data collection in the School of Physiotherapy.

Interested participants were asked to provide their e-mail address and contact phone number to the Clinical Research Administrator of the School of Physiotherapy. A detailed Participant Information Sheet for the ACLR group (Appendix –B7) and Control group (Appendix –B8) was sent to participants by e-mail. Participants who met the initial inclusion criteria were then screened by the PhD candidate, and an appointment was made to book a session in the laboratory to collect data. An online questionnaire link (Qualtrics, Provo, UT, USA, 2015) was sent to participants, who completed the questionnaire (Appendices- C2 to C7) prior to attending the data collection session in the Biomechanics Laboratory. Participants were recruited from 04/2015 to 05/2016.

4.3.5 Sample size estimation

Sample size estimation for this research was performed for the peak knee adduction moment for the ACLR group, and it indicated the need for 26 participants within the ACLR group and 26 in the Control group (Chapter 6, section 6.3.5.1). Muscle strength, physical performance, knee laxity and patient-reported outcomes were examined as secondary outcome measures. This study was an exploratory study in the thesis, therefore, no power calculations were performed; therefore, the results should be considered with caution.

Participants attended two sessions in the laboratory: the first session included data collection relating to the knee laxity measurements and the three-dimensional motion analysis; the second session was for data collection relating to the muscle strength and the physical performance testing.

4.3.6 Inclusion and exclusion criteria

4.3.6.1 Inclusion criteria for ACLR participants

Men and women participants, aged between 20 and 50 years, who had undergone ACLR with any type of graft two to ten years' ago were included in the study. Participants may have had associated ligamentous (such as of medial collateral ligament), meniscal or chondral injury and repair.

4.3.6.2 Exclusion criteria for the ACLR group

Participants with ACLR were excluded if they had only non-surgical rehabilitation, had undergone revision surgery for the ACL injury, had a previous recurrence of ACL injury following the primary reconstruction, or had a bilateral ACL injury. Participants with other lower limb, pelvic or low back musculoskeletal injuries that required health care over the past 6 months, or who were limited their daily function, sports or occupational performance were excluded as well. Pregnant females at the time of data collection were also excluded.

4.3.6.3 Inclusion criteria for the Control group participants

Controls - defined by age, gender, and physical activity (Tegner scores) level-matched participants with no ACL or other knee injury - were recruited.

4.3.6.4 Exclusion criteria for Control group

Participants with knee injuries, lower limb or musculoskeletal injuries that needed health care over the past 12 months or who were limited their daily function, sports or occupational performance, were excluded from the study.

4.3.7 Procedures

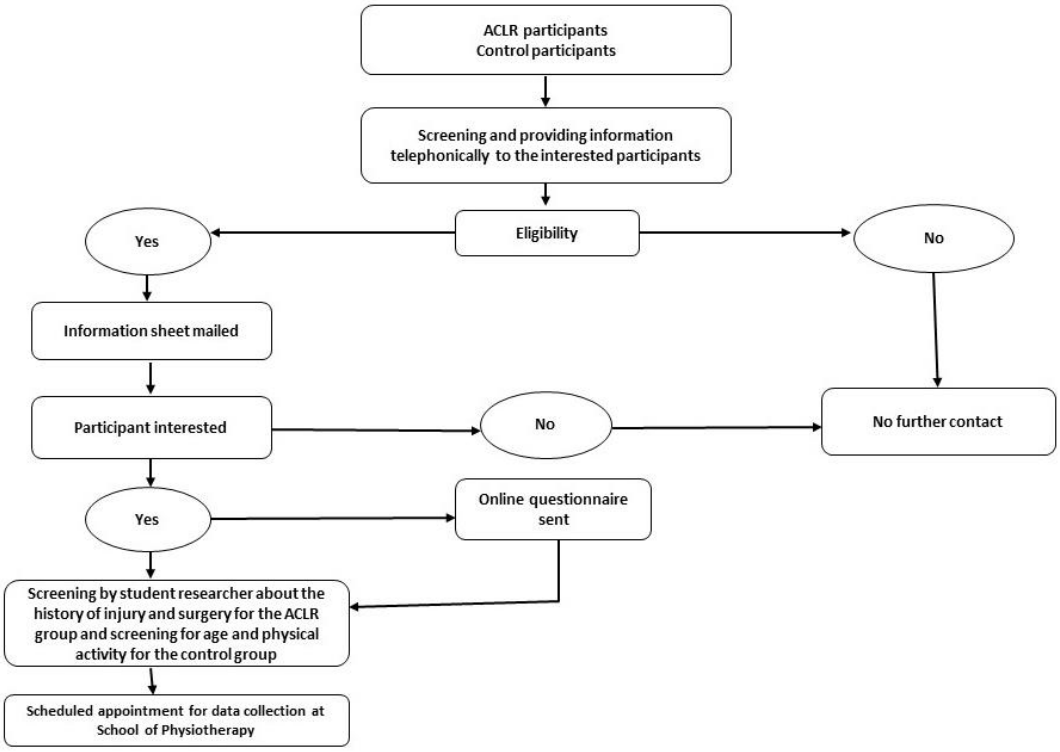


Figure 4.1. Recruitment of ACLR and Control group participants for the study.

The data collection session lasted for approximately 1.5 hours per participant. Participants were introduced to the study and familiarised with the laboratory environment.

4.3.7.1 Patient-reported outcomes

An electronic questionnaire link (Qualtrics, Provo, UT, USA, 2015) was sent to all the participants, comprising of demographic information such as name, profession, ethnicity, year of injury and surgery and patient reported outcome measures. Those patient reported outcome measures included the Tegner score (Tegner & Lysholm, 1985), Activity Rating Scale (Collins, Misra, Felson, Crossley, & Roos, 2011), KOOS (Roos et al., 1998), Confidence in Sports scale (Ardern et al., 2012), SF-12 (Ware Jr et al., 1996)

(Appendices C1 to C4), and were sent to both groups (Figure 4.1). An appointment was made for the data collection as soon as the participants had submitted the questionnaire.

4.3.7.2 Informed consent and Accident Compensation Corporation release form

Following the familiarisation and demonstration of the task, and if participants agreed to take part in the study, they were asked to sign a written, informed consent form. Different consent forms were prepared for the ACLR group (Appendix-B9) and for the Control group (Appendix-B10).

Participants in the ACLR group were asked to sign an ACC Release form (Appendix-B11). The ACC provides comprehensive, no-fault personal injury cover for all New Zealand residents and visitors, and keeps the associated medical and health-related records. Participants provided permission for the researchers to contact ACC to request the following information: date of injury; date of surgery; type of surgery; MRI report (if relevant) to define possible associated injuries of the knee ligament, cartilage or bone; and the number of pre- and post-operative physiotherapy sessions.

4.3.7.3 Muscle strength testing

Peak torque was assessed bilaterally for concentric and eccentric knee extension, and concentric knee flexion, with an isokinetic dynamometer (Biodex Medical Systems, Inc, Shirley, NY) using previously published procedures (Sole, Hamrén, Milosavljevic, Nicholson, & Sullivan, 2007). It is known to have a high relative reliability (Intraclass correlation coefficient range> 0.90) and the smallest real difference of less than 18% (Sole et al., 2007). The test procedure started with the standardised 5-minute general warm-up on a stationary bicycle at moderate intensity.

Participants were seated with the hips in 100° of flexion with their arms resting on their lap. Individual adjustments were made for the seat to accommodate the length of the femur, and for the mechanical axis of the dynamometer lever to be aligned as closely as possible with the anatomical axis of the knee joint. Velcro straps were used to stabilise the participants' trunk, hips and thigh. The distal pad of the dynamometer arm was placed approximately 2 cm above the medial malleolus. The range of movement was from 0° (anatomic 0) to 85° of knee flexion.

Before testing, limb weight was measured using the manufacturer's recommended procedures. Before data collection, participants performed at least five practice trials at sub-maximal level for concentric and eccentric contraction respectively, as part of their familiarisation and as a specific warm-up, followed by two maximal contractions for each type of muscle contraction. A two-minute rest was given after the familiarisation period. The uninjured leg was tested first for participants with ACLR. The dominant leg was tested first, defined as the preferred kicking leg, for the Control group participants.

Participants performed five reciprocal repetitions at 60°/s of maximal extension of each leg (concentric quadriceps) followed by maximal flexion (concentric hamstring) up to 90°. A five-minute rest was given before the contralateral leg was tested. Reciprocal extension and flexion isokinetic testing was done for concentric quadriceps and hamstring, first on both sides, which was to examine the quadriceps (extension) and hamstring (flexion) strength in the same protocol. Participants were requested to use maximal effort by verbal encouragement that they need to "push or pull as hard as they can". Following completion of the reciprocal concentric quadriceps and hamstring set, the eccentric quadriceps strength was assessed at 60°/s with a five-minute rest before starting the next test. Participants were instructed to extend the knee against the shin pad from 90°

knee flexion to full extension, then trigger lever flexion by pressing against the shin pad in the extension direction, and to resist the lever during eccentric extension.

The speed of 60°/sec was chosen for both concentric and eccentric contractions as this is the most commonly used speed in the literature (Undheim et al., 2015). Peak torque was considered as the outcome measure which is the single highest torque output recorded throughout the range of motion of each repetition (Kannus, 1994). Gravity correction of peak torque was made with the Biodex software. Peak torque data was downloaded using the Sys 3 DBM (Version 1.7) system software of Biodex, and was normalised for body weight (Nm/kg). Torque measures in Nm of participants with ACLR have been presented in Appendix C-8.

4.3.7.4 Single-leg hop

The single-leg hop was used as a physical performance measure. This test is known to be reliable in examining neuromuscular function in participants with ACLR (Intraclass correlation coefficient 0.76–.97) (Kramer, Nusca, Fowler, & Webster-Bogaert, 1992). Following the warm up and muscle strength isokinetic testing, the student researcher demonstrated the task of single-leg hop to the participants. Participants were asked to stand on the testing limb with their arms folded across their chest and hop as far as possible. Participants were asked to land on the same limb and maintain their balance for at least 2 seconds following landing. Following the demonstration, participants performed two practice trials for each leg. They then performed three maximal hops for distance for each limb (Gustavsson et al., 2006). Participants wore their own sport shoes. It was important for them to wear the most comfortable shoes which they would prefer for the sports activity in order not to influence the performance. Wearing their own shoes was also considered to increase external validity; that is, reflecting the footwear they use in their daily lives.

The uninjured side was tested first for participants with ACLR, followed by the operated limb. For Control group participants, the dominant limb was tested first followed by the non-dominant limb. An inability to maintain balance was considered to be a disqualification for that trial and the test was repeated. The distance was measured in centimetres from the toe at push-off to the heel where the participant landed. The mean distance across three trials was the outcome measure (Myers, Jenkins, Killian, & Rundquist, 2014).

4.3.7.5 **Knee laxity in sagittal plane**

A KT-1000 arthrometer (MEDmetric® Corp. San Diego, CA, USA) was used to measure the posterior-anterior tibio-femoral laxity of the ACLR and the Control groups in the sagittal plane. The reliability for measuring anterior-posterior tibial displacement relative to the femur has been reported to show substantial variations in measurements (Forster et al., 1989). The specific intra-tester (test-retest) reliability for this measurement was determined by repeating these on a second occasion with 10 participants with ACLR. The Intraclass correlation coefficient was > 0.84, indicating high reliability (Appendix- C6).

Participants were positioned supine with instructions to relax, with their hands resting on their abdomen. Following the manufacturer’s recommendations, a support was placed under the thighs to position the knees in 20° to 30° flexion and it was checked with a goniometer (Fred Sammons, Inc) to ensure that the knee was at the correct angulation. It was maintained approximately at 25°, and a foot support was used to position the feet in a neutral position. A strap around the thighs was used to maintain a neutral rotation position for the hip joints.

The arthrometer was placed with the calibration arrow over the knee joint line and was positioned at the anterior aspect of the tibia and held in place with two Velcro straps, one at the upper end of tibia and other at lower end of tibia. The patellar pad and the tibial pad of the arthrometer were positioned on the patella and tibial tuberosity, respectively. The dial of the arthrometer was aligned to the zero position. The researcher stabilized the patella pad of the arthrometer with one hand, applying even pressure throughout the trial. Following that, the laxity was assessed by applying a manual posterior-anterior force of 30lbs force via the arthrometer handle, guided by an audio tone of the apparatus. The displacement (in mm) measured by the dial was recorded, which was the outcome measure. Each knee was tested four times and the last three readings were documented (Figure 4.2).

Figure 4.2. Positioning and application of KT-Arthrometer

4.3.8 Data processing and analysis

4.3.8.1 **Patient-reported outcomes**

Mean data from the ACLR group were compared with the Control group.

4.3.8.2 **Muscle strength, single-leg hop and knee laxity**

For the ACLR group, data from the injured sides were pooled together. For the Control group, the left and right sides were randomized to Side 1 and Side 2 through the online software, Research Randomizer (Version 4.0) (Urbaniak & Plous, 2013), to generate the numbers for randomization to have the same ratio in terms of right/left sides for the ACLR group.

4.3.8.2.1 Muscle strength

Peak torque was used for the isokinetic muscle strength, and the average distance of three trials was used for the jump distance for the horizontal hop. Limb symmetry was calculated for peak torque of each contraction type: concentric quadriceps, concentric hamstring, eccentric hamstring and for the average jumping distance.

4.3.8.2.2 Single-leg hip

To calculate the limb symmetry index (LSI), the mean scores (5 trials) of the involved limb were divided by the mean score of the uninvolved limb and multiplied by 100 for the hop (Gustavsson et al., 2006). For the healthy participants, the LSI was calculated by the mean scores of side 1 divided by the mean scores of side 2, and the result was multiplied by 100. A LSI greater than 90% was considered to be within the normal range (Gustavsson et al., 2006; Neeter et al., 2006).

4.3.8.2.3 Knee laxity

The average of three trials for each limb for knee laxity was used in the ACLR and Control group. Mean values were utilised, as high variability in the trial was found. This was also based on the previously published papers (Ahldén et al., 2009).

4.3.9 Statistical analysis

SPSS Version 23 (IBM SPSS Statistics) was used for statistical analysis. Normality of the data was tested with histograms and Normal Q-Q plots. Data were found to be normally distributed with histograms, and data points were close to the diagonal line in Q-Q plots.

4.3.9.1 Patient-reported outcomes

Descriptive statistics for all demographic variables and injury factors were reported for groups using means and SD for continuous variables and proportions for categorical variables. Independent t-tests were used to determine the mean differences and 95%CI for the demographic data. The dependent variables were age, body mass index (BMI), Tegner scores, KOOS scale, Activity rating scale, Confidence during sports, and SF-12 Health Survey. An independent t-test was used for each dependent variable. A dependent t-test was used to determine mean differences and 95%CI for the differences in the Tegner scores before injury and after surgery in ACLR group (Table 4.2).

4.3.9.2 Muscle strength, single-leg hop and knee laxity data

A repeated measures analysis of variance (ANOVA, 2 x 2) was used to compare between-group (ACLR versus Control group) and side effects (within-group, injured versus uninjured sides for ACLR group, and Side 1 and Side 2 for the Control group) or interactions effects ($p<0.05$) between ACLR and Control group. Mauchly's Test was used to test the assumption of Sphericity. Pairwise post-hoc tests were performed to analyse the side differences among the groups if significant effects or interactions were found. A Bonferroni test was used for the pair-wise comparisons. The Bonferroni method is considered to be a robust method and able to control alpha levels, and reduces the chances of a Type 1 error (Field, 2009). Effect sizes (Cohen's d) were calculated for the significant differences, and categorised as small (b0.5), medium (≥0.5 and b0.8) or large (≥0.8) (Cohen, 1988).

4.4 Results

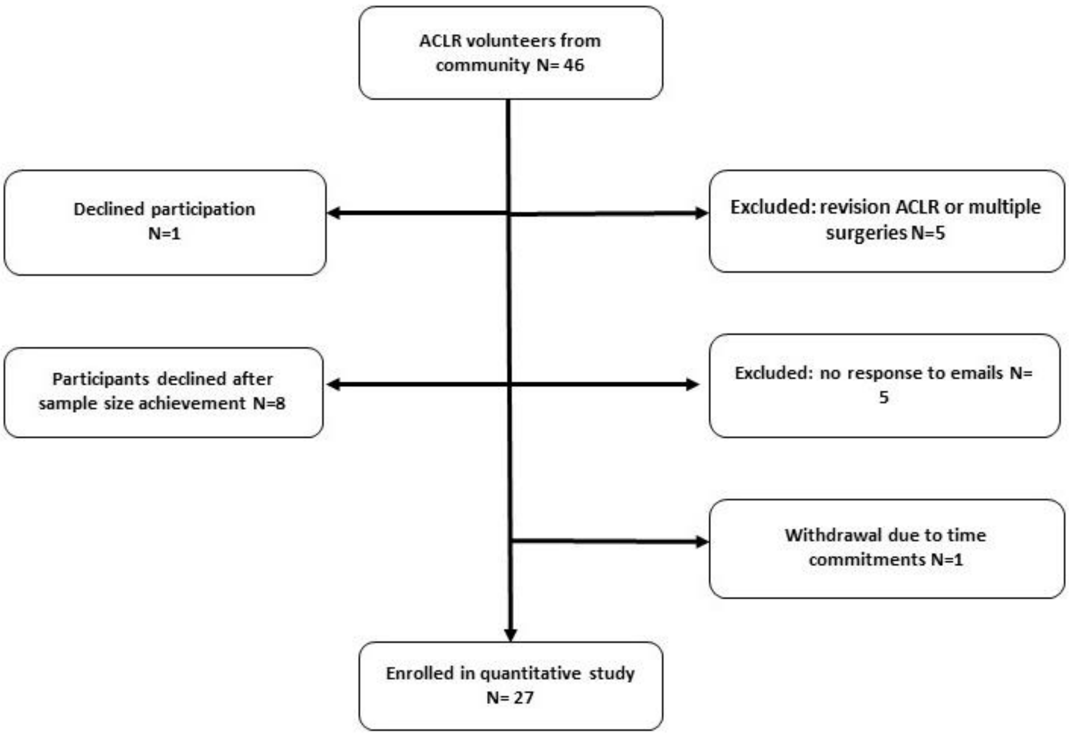


Figure 4.3. Flow of participants with ACLR in the study.

A total of 46 individuals with unilateral ACLR showed an interest in taking part in the study. Data from 27 participants with ACLR were collected, and reasons for not participating are provided in Figure 4.3. Similarly, a total of 44 Control group participants volunteered for the study and data from 25 participants were finally collected Figure 4.4. Data of 1 participant in the Control group was excluded due to inter-limb differences in the knee laxity and different movement pattern during stair descent, leading to final data of 24 participants.

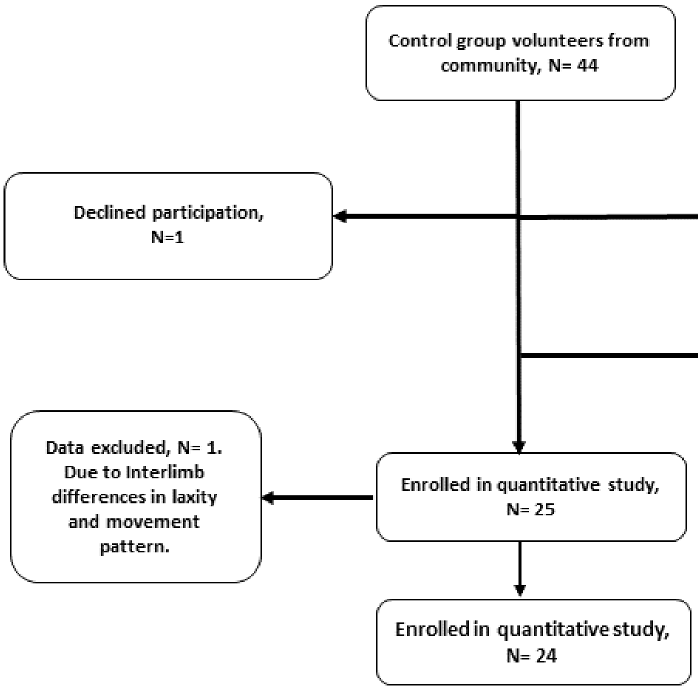


Figure 4.4. Flow of Control group participants in the study.

Isokinetic muscle strength and single-leg hop data for 3 participants was missing: one participant could not undertake the muscle strength testing due to the onset of knee pain following the Biomechanical data collection; two further participants did not attend the session evaluating the muscle strength and the single-leg hop, although e-mail reminders were sent to them. Reasons for withdrawing from the muscle strength data collection for these two participants are not known. The total number of participants included in the analysis for muscle strength and the physical performance test was 22 for the ACLR group and 24 for the Control group.

4.4.1 Data provided by ACC

The ACC provided the data for 21 participants with ACLR, confirming the dates of injury and surgery (Appendix-C7). Data was also provided by the participants that related to type of surgery and graft. Participants had attended, on average, 13 pre-operative (range 1-27) and 14 post-surgery physiotherapy treatments (range 1-48).

4.4.2 Patient-reported outcomes

Patient-reported outcomes of the ACLR group were compared to the Control group. Participants with ACLR were from 2 to 10 (mean 4.7) years following surgery. Information related to time since surgery and time between injury and surgery has been presented in Appendix C9. Significant between-group differences were found for BMI, with higher mean scores in the ACLR group ($p<0.001$) compared with the Control group (Table 4.1). Results from the patient-reported outcomes indicated no difference in the level of physical activity (Tegner scores, Table 4.2). The participants of this study were a mixed cohort with athletic and non-athletic participants in both the ACLR and Control group.

Table 4.1. Participant characteristics

	ACLR (SD)	Control (SD)	p-value
Men/Women (n)	25 (13W)	24 (13W)	
Age (years)	30.8 (9.7)	31.4 (10)	0.829
BMI (kg/m^2)	26.6 (3.6)	22.7 (3.6)	<0.001
Injured side	18 left/7 right	_	
Limb dominancy	22 Right dominant	23 Right dominant	
Time since ACLR (years)	4.7 (1.8) (range 2 to 10)	_	
Graft types	PT- 36% HT-56% Unknown-8%		
Meniscal injuries	40%		

n= Number, ACLR= Anterior cruciate ligament reconstruction, BMI= Body mass index, SD= Standard deviation, PT= Patellar tendon, HT= Hamstring tendon graft, W=Women. Data indicate mean and standard deviation for the participant characteristics.

For the KOOS, the largest differences were seen for the Sports/Recreation function (ACLR: 75.8; controls: 98.0, p = <0.001, Table 4.2) and knee-related QOL (ACLR: 47.0; controls: 80.4, p = <0.001). Significant differences were also found in $KOOS_4$ scores with lower scores in the ACLR group (mean= 65.6) compared to the Control group (86.5). Participants with ACLR scored low (mean= 42.6) on the Confidence during sports scale. Data from four control participants was missing for the Confidence during Sports scale due to a technical error in the online questionnaire response section, therefore this data was not compared to the Control group of this study.

From the results of SF-12, there were significant differences in the Physical Component Summary score among the ACLR and Control group. The ACLR group had lower scores on the Physical Component Summary compared to the Control group. No significant differences were found between the groups for the Mental Component Summary Scores.

Table 4.2. The ACLR group scored significantly worse in all five dimensions of the KOOS and Physical component of SF-12 Health survey

	ACLR	Control	p-value	Effect size	Mean difference (95% CI)
Tegner activity scale (0 to 10)(n, ACLR= 25, Control=24)					
Before injury	6.9	N.A.			
Current	5.4 (2.5)	4.3 (1.7)	0.090		1.1 (1.8-2.3)
KOOS Scale (0 to 100)(n, ACLR= 25, Control=24)					
Pain	85.3 (11.9)	98.9 (2.3)	**<0.001**	0.96	13.3 (8.3-18.4)
Symptoms	54.5 (12.2)	67.2 (7.4)	**<0.001**	0.65	12.6 (6.8-18.5)
Function in daily living	95.0 (7.4)	99.7 (0.8)	**0.003**	0.57	4.7 (1.6-7.8)
Function in sports and recreation	75.8 (14.8)	98.0 (2.7)	**<0.001**	1.27	22.7 (16.54-28.9)
Knee-related quality of life	47.0 (19.7)	80.4 (8.5)	**<0.001**	1.18	33.4 (24.6-42.2)
KOOS$_4$	65.6 (11.37)	86.5 (4.19)	**<0.001**	1.34	20. 9 (15.9-25.8)
Confidence during sports (0 to 80) (n, ACLR= 25)					
Confidence during sports	42.6 (10.63)	–	–		–
SF-12 Health Survey (0 to 100)(n, ACLR= 25, Control=24)					
PCS	53.9 (4.0)	56.9 (3.2)	**0.008**	0.42	2.9 (0.8-5.0)
MCS	52.4 (5.5)	50.8 (7.7)	0.418	0.12	1.5 (5.4- 2.3)

ACLR= Anterior cruciate ligament reconstruction, CI: Confidence interval, KOOS= Knee Osteoarthritis Outcome Scale, Short Form-12 Health Survey, MD: Mean difference, PCS= Physical Component Summary, MCS= Mental Component Summary.

4.4.3 Muscle strength

4.4.3.1 Concentric quadriceps peak torque

No group or side effects were found for peak torques for concentric and quadriceps. A significant group x side interaction (p <0.001) was found for concentric quadriceps peak torque between the ACLR and Control group (p<0.001) (Table 4.3, Figure 4.5). Post-hoc analyses indicated lower peak strength in the ACL injured side compared to the side 1 of the Control group [mean difference 0.44 Nm/kg (95%CI): 0.01-0.88, p=0.043] (Table 4.4). For the ACLR group, the LSI for concentric quadriceps peak torque was 88% while that of the Controls was 106%.

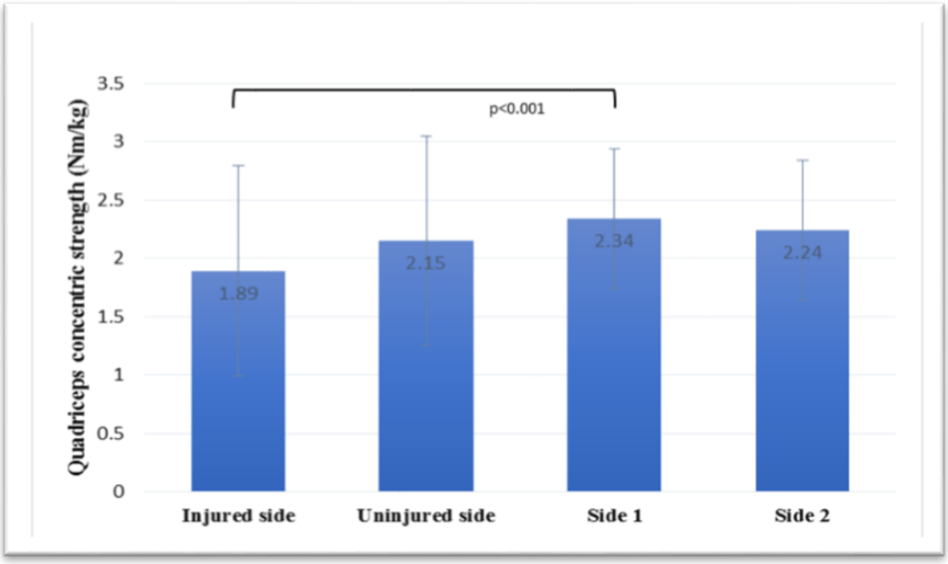


Figure 4.5. Differences in the quadriceps concentric strength between ACLR and Control group.

4.4.3.2 Eccentric quadriceps peak torque

Significant side effects were found for quadriceps eccentric peak torque (p = 0.004) (Table 4.3, figure 4.6). Post-hoc pairwise comparisons for quadriceps eccentric peak torque found lower peak torque on the injured side compared to the contralateral limb (mean difference 0.31nm/kg, 95%CI 0.10-0.53, p=0.004) for the ACLR group. For the ACLR group, the LSI for concentric quadriceps peak torque was 89% while that of the controls was 95%.

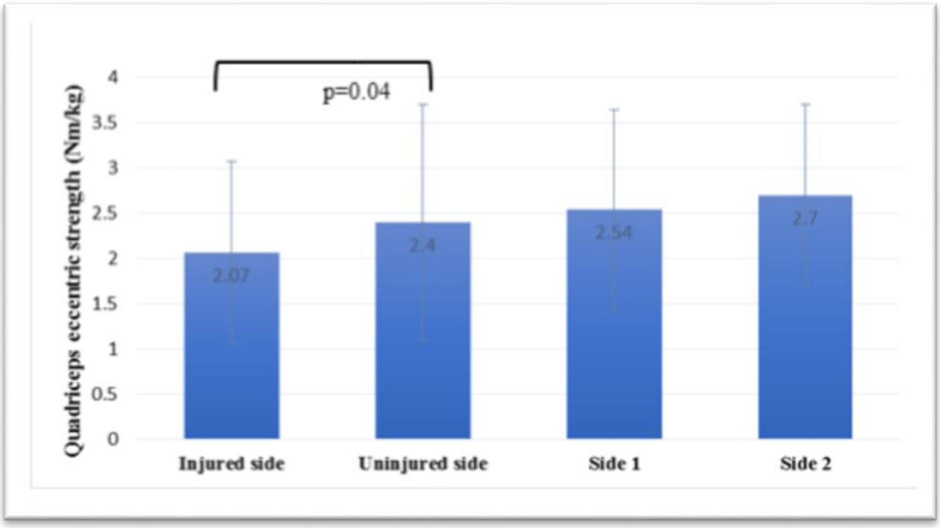


Figure 4.6. Differences in quadriceps eccentric strength between ACLR and Control group.

4.4.3.3 Concentric hamstring peak torque

Significant side effects were found for hamstring concentric peak torque (p=0.019) (Figure 4.7) while the group effects were not significant. The ACLR injured sides had significantly lower concentric hamstring peak torque than the uninjured sides (p=0.019). A significant group x side interaction (p=0.045) were found for hamstring concentric strength (Figure 4.8) although the post-hoc comparisons were not significant. Post-hoc pairwise comparisons showed significantly lower peak torque for concentric hamstring (mean difference 0.05 nm/kg (95%CI): 0.03-0.15, p=0.003) for the injured side compared to the contralateral limb in the ACLR group. For the ACLR group, the mean LSI for concentric quadriceps peak torque was 92% while that of the controls was 101%.

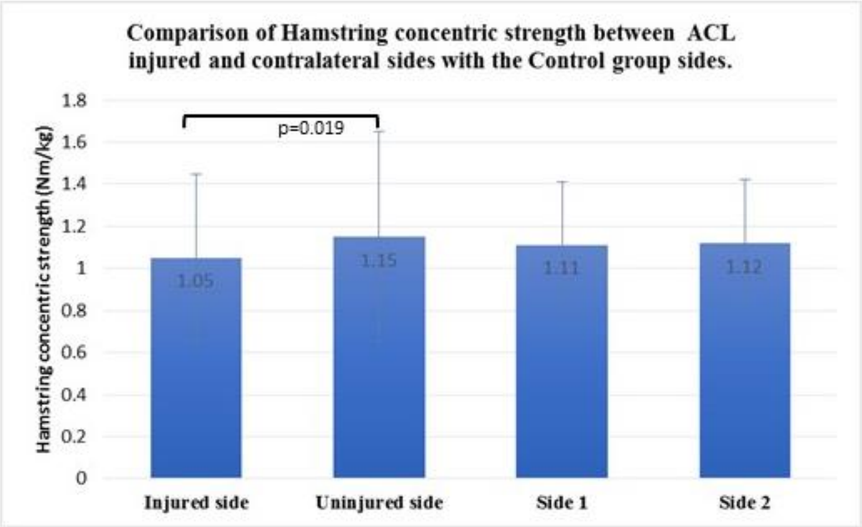


Figure 4.7. Differences in hamstring concentric strength between ACLR and Control group.

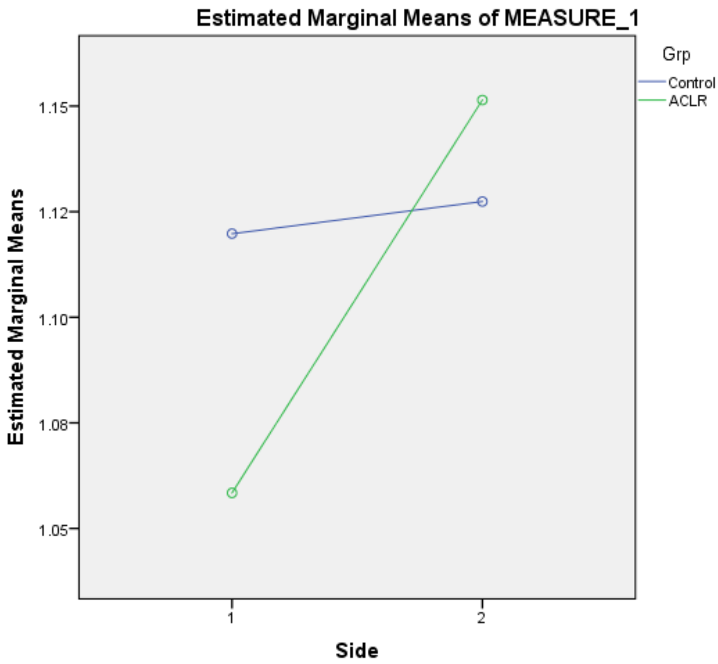


Figure 4.8. Group x Side interaction for the groups for hamstring concentric peak torque. Side 1 is ACL reconstructed in ACLR group.

Table 4.3. Differences in muscle strength, single-leg hop, knee laxity among ACLR and Control group

	ACLR group (Mean (SD))			Control group (Mean (SD))					
	Side 1 (Injured side)	**Side 2 (Uninjured side)**	**LSI%**	**Side 1**	**Side 2**	**LSI%**	**Group effect**	**Side effect**	**Group* side interaction**
Peak torque (Nm/kg) (n, ACLR= 22, Control=24)									
Quadriceps concentric	1.89 (0.9) *	2.15 (0.9)	87.5 (14.1)	2.34 (0.6)*	2.24 (0.6)	105.9 (15.0)	0.213	0.095	**<0.001**
Quadriceps eccentric	2.07 (1.0) #	2.40 (1.3) #	89.1 (18.2)	2.54 (1.1)	2.70 (1.0)	95.1 (15.0)	0.265	**0.004**	0.200
Hamstring concentric	1.05 (0.4) #	1.15 (0.5) #	92.4 (10.9)	1.11 (0.3)	1.12 (0.3)	101.2 (16.8)	0.869	**0.019**	**0.045**
Single-leg hop (Centimetres, ACLR=22, Control=24)									
Jump distance	104.7 (30.1) #*	114.7 (26.0) #	90.69 (14.2)	98.8 (21.6)	96.7 (21.1) *	102.23 (9.56)	0.101	**0.026#**	**0.001**
Knee laxity in sagittal plane (mm) (n, ACLR=25, Control=24)									
Knee laxity	6.87 (2.7) #*	5.13 (2.0) #∞	_	4.50 (1.7) *	4.83 (1.8) ∞	_	**0.011**	**0.027#**	**0.001**

ACLR: anterior cruciate ligament reconstruction. Group × side interaction indicates that there is a statistically significant difference between the sides and the group, that is, the difference between the two sides differs between the three groups. Group: there is a statistically significant difference between the values for the three different groups. Sides: there is a statistically significant difference between the two sides. Significant differences between sides, $p < 0.05$; SD Standard deviation; * Significant difference between group sides; # significant difference present between both sides; ∞ significant difference between groups;

Table 4.4. Results of post-hoc testing the ACLR and Control groups.

	Control Side 1 versus Side 2		**ACLR injured side versus Controls side 1**		**ACLR injured versus contralateral side**		**ACLR uninjured side versus Controls side 2**	
	Mean difference (95%CI) and ES	p-value	Mean difference (95%CI) and ES	p-value	Mean difference (95%CI) and ES	p-value	Mean difference (95%CI) and ES	p-value
Muscle strength (Nm/kg)								
Quadriceps concentric			0.44 (0.01-0.88) ES: 0.30	0.043	0.75 (0.01-0.16) ES 0.04	0.095	0.09 (0.35-0.53) ES: 0.06	0.684
Quadriceps eccentric	0.127 (0.08-0.33) ES: 0.08	0.232	_		0.31 (0.10-0.53) ES: 0.14	0.004	_	_
Hamstring concentric	0.008 (0.05-0.67) ES: 0.02	0.796	0.61 (0.16-0.28) ES: 0.09	0.581	0.05 (0.03-0.15) ES: 0.11	0.003	0.02 (0.21-0.26) ES: 0.04	0.840
Jump distance (cm)								
Jump distance	2.07 (2.7-6.9) ES: 0.05	0.390	_		10.07 (5.03- 15.11) ES: 0.18	< 0.001	18.00 (4.00-32.00) ES: 0.38	0.013
Knee laxity in sagittal plane (mm)								
Knee laxity	0.061 (0.82-0.94) ES: 0.09	0.891	2.24 (0.92-3.60) ES: 0.54	0.001	1.73 (0.87- 2.60) ES: 0.37	<0.001	0.44 (0.62-1.05), ES: 0.08	0.407

ES: effect sizes, Cohen's d, p-values obtained with Bonferroni's corrections.

4.4.4 Single-leg hop

No significant group effects were found for jump distances among the ACLR and Control group (Table 4.3), but side effects were significant. Post-hoc pairwise comparisons indicated a significant side-to-side difference for the ACLR group with a shorter distance jumped by the injured side compared to the contralateral limb (mean difference 10.07, 95%CI 5.03- 15.11, $p < 0.001$)(Table 4.4). The group x side interaction was also significant. Pairwise comparisons indicated a higher mean jump distance on the uninjured side of ACLR group compared to the Side 2 of the Control group (18.00, 95% CI 4.00-32.00, p=0.013) but a shorter distance for the ACLR injured side compared to the Control Side 1 (Figure 4.9).

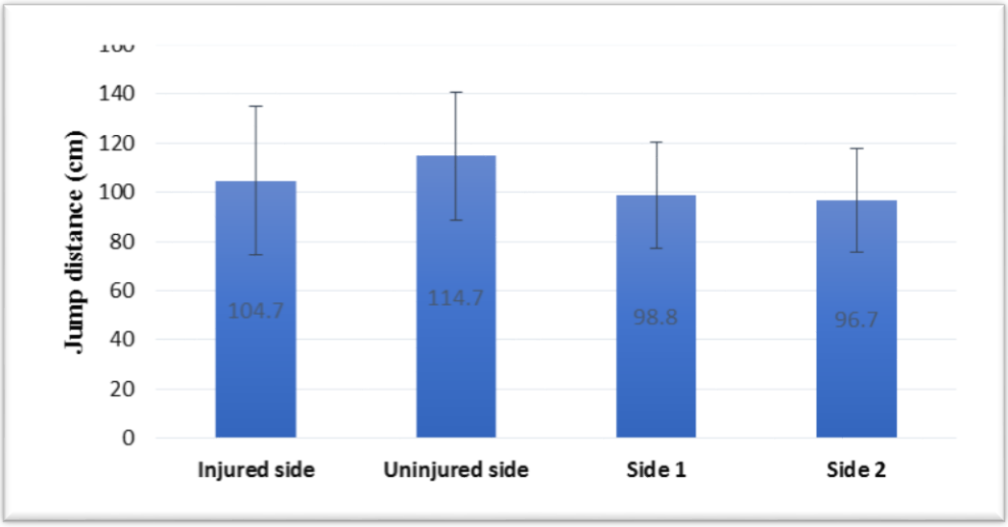


Figure 4.9. Differences in single-leg hop performance between ACLR and Control group.

4.4.5 Knee laxity in sagittal plane

Significant group ($p = 0.011$) and side ($p = 0.027$) effects and a significant group x side interaction were found for knee laxity in the sagittal plane (Table 4.3) (Figure 4.10). Post-hoc pairwise comparisons indicated higher laxity for the injured side compared to the contralateral limb in ACLR group (mean difference 1.73, 95%CI 0.87- 2.60, p<0.001) (Table 4.4). Significantly higher knee laxity was also found when comparing the ACL injured side compared to the Control side 1 of Control group (mean difference 2.24 (95%CI): 0.92-3.60, p=0.001), while no differences were found between the contralateral side of the ACLR group compared to side 2 of the Control group. Test-retest reliability for the KT-arthrometer was found to be ICC- 0.86 was reported, with a standard error of measurement 2.2 mm (Appendix-C6).

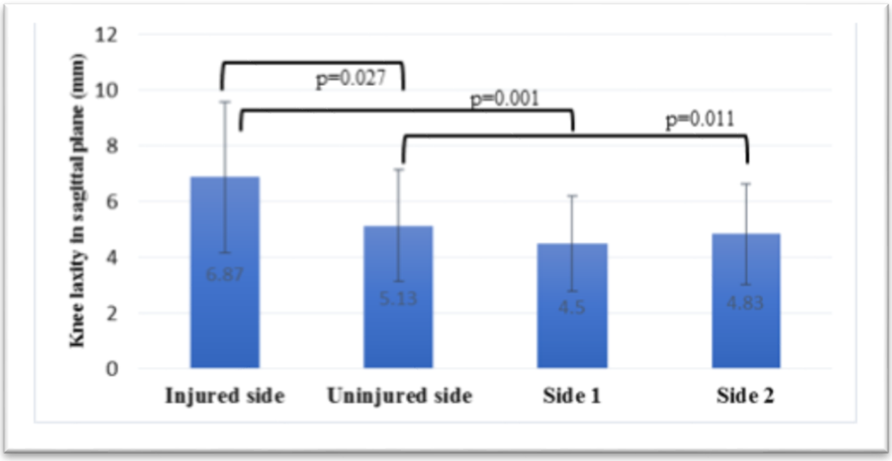


Figure 4.10. Differences in knee laxity between ACLR and Control group.

4.5 Discussion

The aim of this study was to compare the patient-reported outcomes among the ACLR and Control groups. Muscle strength, physical performance and knee laxity of the injured side in participants with ACLR were compared with those of the contralateral limb, and with the Control group. Participants had statistically significant differences for all sub-scales of KOOS, Physical Component of SF-12 and Confidence during Sports compared to the Control group. The ACLR injured side was weaker when compared to the contralateral side and to the Controls. Physical performance on the contralateral side was higher than the control side 1. Higher laxity was present in the ACLR group on the injured side compared to the contralateral side and to the Control group.

4.5.1 Patient-reported outcomes

There were significant differences in all subscales of the KOOS scores with ACLR group experiencing more pain, symptoms, lower levels of knee function in daily life and sports, and lower quality of life compared to the Control group, but there was no significant difference between the level of physical activities among both groups (Tegner scores). The KOOS scores in all subscales ACLR group were lower than the ‘acceptable state’ scores as given by the (Muller et al., 2016). This finding may be due to the older age (mean 30.5 years) and greater time following surgery (4.7 years) for participants in the current study, compared to participants in the Muller study (mean age 26.2 years, and 3.4 years following ACLR). One of the goals for the management of the injury is to optimise the quality of life in the long-term. However, this goal doesn’t seem to be fully accomplished in this group of participants. The presence of symptoms has been negatively correlated with levels of satisfaction (Kocher et al., 2002). This group of participants still reported experiencing knee-related symptoms (KOOS symptoms= 54.5/100), which may have affected their perceptions about their quality of life, defined as the expectations of health versus actual experience (Carr, Gibson, & Robinson, 2001). As participants of this study were relatively young (median, 28.5 years), their health expectations may be high, which, in turn, may have influenced their rating of current quality of life, as defined by the KOOS QOL scores (47.0/100) and the PCS of SF-12.

A previous study has reported quality of life for participants 12 to 14 years following ACL injury with visible radiographic changes for knee osteoarthrosis (Von Porat et al., 2004). They indicated mean (SD) scores for KOOS QOL of 60 (24.6) and 63 (28.7) for KOOS function in sports and recreation. While the mean KOOS QOL in the current study was lower than that (47.0), the mean KOOS function in sports and recreation score of 75.8 (14.8) indicated that our participants were more active in sports and recreational activities, and had better knee function in their daily life activities compared to the above-mentioned study. The KOOS results were also supported by the SF -12 Physical Component Summary scores, which were significantly lower for the ACLR group than the Control group (ACLR= 53.9, Control= 56.9, p=0.008). Knee-related quality of life scores of the participants of this study (KOOS QOL mean score = 47) were comparable to those of the participants with knee osteoarthritis (KOOS QOL mean score = 50.0) (Aksekili et al., 2016). Those participants had knee osteoarthritis classified as Grades 2 or 3 on the Kellgren-Lawrence scale. Participants in our study had less pain (mean= 85.3) and more knee-related symptoms (mean= 54.5) compared with the participants with knee osteoarthritis pain (mean= 60.0) and knee-related symptoms (mean= 71.4). However, interestingly, despite lower levels of knee function (KOOS ADL score 70 versus 95), the quality of life was similar in both groups (Aksekili et al., 2016). The similarity in the quality of life in both groups could be attributed to their different levels of sports recreational activities, and their preferences and expectations from life. Furthermore, based on findings of knee osteoarthritis being evident as soon as 5 years following ACL injury or surgery (Wellsandt et al., 2016), it is possible that some of the participants with ACLR already exhibited knee osteoarthritis in one or more compartments. However, as no investigatory procedures such as X-ray and MRI were performed, it is a speculation.

The participants with ACLR, on average 4.5 years following surgery (range 2–10), appeared to have continued low confidence in the injured knee during sports, despite indicating good function in sports and daily living (KOOS: sports and recreation mean=

76/100), and mean Tegner scores post-injury (6). It is difficult to speculate on the reasons for reduced confidence level in sports from this study; however, it is important to investigate as reduced levels in confidence can affect performance levels in sports (Ardern et al., 2012). Lower confidence during sports may be related to fear of re-injury, exacerbating symptoms, and reduced physical function (Hart, Collins, Ackland, & Crossley, 2015). Therefore, improving confidence in the knee may relieve knee symptoms and enhance physical function in this group of participants.

SF12 scores were compared to the national averages of the South Australian data using a PCS of 52.5 and MCS of 52.4 as the cut-off for an individual's score based on the standard error of measurement ± 6.97 (Utah Health Status Survey, 2001). The PCS scores of the ACLR group (53.9 (4.0) in the current study were similar to those figures, (Quality of life in Southern Australia, 2005). The SF scores can vary based on the underlying conditions such as arthritis, high blood pressure, high cholesterol, overweight and obesity, smoking and high risk alcohol use. We did not account for the above-mentioned factors.

4.5.2 Muscle strength

According to our results participants had strength deficits on the injured side compared to the contralateral limb, and the ACLR injured side had weaker concentric quadriceps peak torque compared to the controls. Deficits in knee extension strength have been reported by a recent study with participants at 2.5 years on an average following surgery. Strength deficits of 6 to 9% were found in the involved leg compared to the uninvolved leg. These deficits were small compared to the other studies in the literature, and were considered due to an incomplete rehabilitation of the ACLR knee and/or the inability to fully activate the muscle as a result of the initial and post-operative joint damage (Otzel et al., 2015). Participants in our study were from 2 to 10 years from surgery and were a mixed-cohort from the community varying from sedentary to physically active life-styles. Therefore, it is difficult to comment on the reasons for the present muscle strength deficits. Deficits are most pronounced in the concentric quadriceps muscle strength and the least in the knee flexor muscle group. This is similar to another study where 10% strength deficits were found in the concentric knee extension group 4-7 years following surgery (Moisala et al., 2007). Results of our study can also be compared to another study exploring the outcomes of ACLR at 20 years following surgery and had similar peak torque values for the knee flexor and extensor strength (normalised to body weight). That study indicated the presence of concentric and eccentric quadriceps and hamstring strength deficits (Tengman et al., 2014). The LSI values of our study for quadriceps concentric and eccentric values (87 % and 89% respectively) were similar to the mean values, with values of (89% and 86%, respectively) Tengman et al., 2014. Similarly, the LSI for concentric hamstring in our study was 92.4% and for the control group was 101%. Though the participants of the Tengman study had a mean age of 45 years, which is higher than our study participants (mean age 30.8), the extent of physical impairment is similar. It may mean that impairments may not recover with time. Ninety percent symmetry in quadriceps (and hamstring) strength was recently identified by a consensus as a measure important for achieving successful outcome after ACLR (Lynch et al., 2013). Our cohort had symmetry in the concentric hamstring muscle strength; however, it was lower for concentric and eccentric quadriceps strength. Previously rehabilitation programs including aggressive quadriceps strengthening and perturbation training have been proven successful in restoring limb symmetries (Logerstedt, Lynch, Axe, & Snyder-Mackler, 2013). The participants of the current study are from mid- to long-term following surgery, therefore, it needs to be explored further if the similar rehabilitation protocol can help to restore the symmetry at this stage.

Reduced muscle strength can be due to complex interaction between various components of the body, for instance, there is reduced proprioception following the surgery at the knee (Bonfim et al., 2003), along with less activation of the sensory cortex (Valeriani et al., 1996). There is lower activation of quadriceps muscle following the ACL injury and surgery (Hart et al., 2010), which is thought to be due to the alterations of corticomotor excitability (Pietrosimone et al., 2012). Changes in the central nervous system are supported by more recent findings of reduced activation of the ipsilateral motor cortex following ACL injury (Grooms et al., 2017). Although the ruptured ligament may be repaired with a graft, complex interaction and deficit seen at the muscular, neural and central nervous system level is perhaps not fully restored to optimal levels. Therefore, management should not focus on muscle strength training only, as there is need of an exercise protocol enhancing the link between the joint, muscle, and central nervous system.

Muscle strength deficits may be a risk factor for post-traumatic osteoarthritis (Oiestad, Holm, Gunderson, Myklebust, & Risberg, 2010). Keays et al., 2007 followed participants with ACLR from 6 months to 6 years following surgery, and found a 6% deficit in quadriceps muscle strength in those who had undergone patellar tendon grafts. The quadriceps deficit appeared to be associated with radiographic evidence of knee osteoarthritis. Similarly, reduced joint space width was found in participants with lower concentric quadriceps and hamstring muscle strength following surgery ACLR, on average 4 years following surgery (Tourville et al., 2014). An association between quadriceps muscle strength and primary osteoarthritis is already known (Farr et al., 2010; Mihelic, Jurdana, Jotanovic, Madjarevic, & Tudor, 2011; Palmieri-Smith, Thomas, Karvonen-Gutierrez, & Sowers, 2010). Therefore, lower muscle strength could potentially be a risk factor for osteoarthritis in this group of participants. Our study found between-side differences of 5% for concentric hamstring and 22.3% for eccentric quadriceps in the ACLR group (2 to 10 years following surgery). While we did not examine radiographic changes related to osteoarthritis, the question is raised whether these muscle deficits, particularly for the eccentric quadriceps strength could be a marker for future knee osteoarthritis.

4.5.3 Single-leg hop

The participants with ACLR hopped a shorter distance on the injured side compared to the uninjured side. The LSI for the ACLR was 90%, whereas LSI for the Control group was 102%. Their hop distance for the uninjured side, however, was significantly longer compared to the Control group side 2. The jump distances of our study are similar to hop distance in another study (Injured side= 112.0 cm, Contralateral side= 119.0 cm) exploring the functional outcomes in participants with ACLR 20 years following surgery (Tengman et al., 2014). Participants of that study were of higher age group (mean=45 years) but had similar level of Physical activity levels (Tegner score=4), which may be responsible for the similarity in the results. The lower jump distance on the injured side indicate the preference of participants for less loading activities on the injured side; which may represent the consequences of the surgery as the contralateral side had the higher jump capacity.

In another study, participants with poor muscle strength (<85%) performed poorly during the hop test compared with participants with good muscle strength (>90%) and an uninjured Control group (Schmitt, Paterno, & Hewett, 2012), indicating an association between jump performance and muscle strength. Other factors such as reduced proprioception, fear of injury, hesitation during weight bearing, and lower confidence in this group of participants may also have contributed towards the single-leg hop LSI.

Muscle weakness, particularly eccentric muscle strength, is required to control the limb during landing following the jump. The eccentric quadriceps deficit found in these participants may thus have contributed to, or be associated with, the reduced hop distance. Similar conclusions may be drawn relating to the sports- related task during competitive sports.

4.5.4 Knee laxity in the sagittal plane

Participants with ACLR had higher laxity on the injured side compared to the contralateral side and the Control group. The standard error of measurement (SEM) for KT-Arthrometer was 2.2 mm, and the side-to-side mean difference for the ACLR group is less than the SEM, therefore, the side to side differences found in the study should be considered with caution. However, the mean differences were greater than the SEM for the mean difference between the injured side and the side 2 of the Control group. Higher laxity on the injured side is considered multifactorial and may be due to the type of graft, change in the graft tension over time, preconditioning of the graft (Ejerhed et al., 2001) and positioning of the tunnel at the time of surgery (Rayan et al., 2015). In the present study, we were unable to control for the above-mentioned factors. Participants with different grafts were included in the study which could have influenced the findings of the study. Our results are in contrast to previous studies that have either reported the reduced sagittal plane tibio-femoral laxity at 7 years following surgery (Ahldén et al., 2009), or have reported no change in the graft laxity over time from mid- to long-term following surgery (Salmon et al., 2006; Shelbourne et al., 1995). Higher laxity may potentially reduce the stability of the joint and can make the joint vulnerable to the physical stresses experienced during ambulatory activities, which can be a major risk factor for osteoarthritis. Theoretically, joint laxity observed may be controlled by muscle action.

However, as no EMG for the thigh muscles was performed, it is difficult to comment on whether the muscles were controlling the increased knee laxity in this group of participants

Taken together, higher laxity with poor muscle strength and poor performance in the single-leg hop in participants with the ACLR persist in the mid- to long-term following surgery, and indicate the presence of physical impairment which can, potentially, be responsible for the onset and progression of osteoarthritis.

4.5.5 Limitations

Outcomes of surgery may be dependent on the graft type (Spindler et al., 2004). As the participants were recruited from the community, we could not control for the type of graft in the study participants. Due to the cross-sectional design, all measurements were taken only at one-time point. Thus, the influence of time following ACLR on the included variables cannot be established. Higher laxity on the contralateral knee compared to the Control group side 2 indicates potential generalised higher laxity in ACLR group. For the physical performance, only a single-leg hop test was used instead of a battery of tests. However, this test is known to be reliable either used alone or along with the battery of tests (Palmieri-Smith & Lepley, 2015). Moreover, as this test is only analysing the performance of one limb at a time, it reduces the chances of compensatory strategies by the contralateral limb during execution of the test. Participants were at different levels of physical activity varying from a Tegner score of 9 (competitive sports like soccer, ice hockey) to as low as 3 (competitive and recreational sports like swimming). This could have led to some dilution in the average scores of the ‘confidence during sports’ scale. However, it is already known that those who return to sports have less fear of injury (Ardern et al., 2012).

4.6 Conclusions

Differences in patient-reported outcomes, muscle strength, physical performance, and knee laxity were evident in ACLR cohort compared to Control group. These physical impairments indicate suboptimal joint function along with a lower quality of life compared to the age- and gender-matched Control group. Higher laxity may potentially reduce the stability of the joint and can make the joint vulnerable to the physical stresses experienced during ambulatory activities, which can be a major risk factor for osteoarthritis.

4.7 Summary

This chapter presented and discussed the physical impairments in participants with ACLR up to 10 years following surgery. Participants also experienced low confidence levels during sports and a poor quality of life compared to the age- and gender-matched controls. The next study (Chapter 5) explored the participants' perspectives of the outcomes of ACLR relating to their life.

5 Participants' perspectives of the outcome of anterior cruciate ligament (ACL) reconstruction surgery: a mixed-method study.

5.1 Prelude to Chapter 5

This mixed-method study provided an in-depth understanding of participants' concerns and experiences of the outcomes of ACLR. This study highlighted the factors related to fear of re-injury, reduced confidence in the injured limb during sports, hesitancy in weight bearing on the injured side and participants' daily struggles related to activities of daily life. These are important findings for the patients and clinicians as it can lead to longer-term deficits and biomechanical implications.

Chapter 5

5.2 Background

There appears to be a trend for increasing number of patients choosing ACLR over non-surgical rehabilitation only (Sanders et al., 2016). Most patients undergo ACLR with the intention to return to sports (Heijne et al., 2008; Thing, 2006), however, only 55% are able to return to competitive sports (Ardern et al., 2014). Participants may continue to play for approximately 2 years and thereafter often tend to change to a lower level of sports (Ardern et al., 2014; Smith, Rosenlund, Aune, MacLean, & Hillis, 2004) due to various reasons, such as fear of re-injury and changed life or occupational commitments (Doyle, Wilson, & King, 2013; Kvist, Ek, Sporrstedt, & Good, 2005). Those who continue to play competitive sport appear to report lower knee-related quality of life in the long-term (up to 20 years post-ACLR) than those who have changed to recreational-level sports (Filbay et al., 2016). Decision making regarding continuation of level of sports participation thus appears to be one of the factors influencing the reported quality of life.

Knee injuries have been reported to decrease knee-specific function and health-related quality of life in collegiate athletes (Lam, Thomas, Valier, McLeod, & Bay, 2015). Furthermore, development of osteoarthritis also impacts the health-related quality of life in general (Salaffi, Carotti, Stancati, & Grassi, 2005; Turner, Barlow, & Heathcote-Elliott, 2000). Different results have been reported regarding the health-related quality of life in participants with ACLR, varying from low at an average of 5 years (Filbay, Ackerman, Russell, Macri, & Crossley, 2014), to that of similar quality of life to uninjured controls at an average of 11.5 years post-surgery (Möller et al., 2009) as discussed in Chapter 2 section 2.6.2.

Outcomes of an intervention are usually considered in terms of restoration or improvement of individual-specific function related to activities of daily life (ADL), sports, recreation and occupation-related demands (Tanner, Dainty, Marx, & Kirkley, 2007). Understanding the individual patients' perspectives of outcomes of ACLR is a key concept of patient-centered care (Epstein & Street, 2011). A recent qualitative study with the participants up to 3 years following ACLR indicated that recovering from an ACL injury experience was a long, arduous and disruptive "journey" influencing their individual identity (Scott et al., 2017). To improve our understanding of outcomes of ACL injury and reconstruction, the aim of the present study was to explore the participants' experiences of the outcomes of their surgery more than 2 years following surgery in relation to physical activity, sports, occupation and health-related quality of life.

5.3 Methods

5.3.1 Study Design

This is a mixed-method study design with patient-reported outcome measures and semi-structured interviews. Consolidated Criterion for Reporting Qualitative Research (COREQ) checklist was used for reporting the study (Tong, Sainsbury, & Craig, 2007). Prior to the beginning of the study, researchers bracketed their perceptions and thoughts related to the field of the study. Bracketing in descriptive phenomenology entails researchers setting aside their pre-understanding and acting non-judgmentally along with adding scientific rigour (Sorsa, Kiikkala, & Åstedt-Kurki, 2015)(Appendix-D1). Moreover, a phenomenological approach to data was followed, where bracketing is considered important.

5.3.2 Recruitment, inclusion and exclusion criteria for the study

Participants were recruited from the local community via advertisements for quantitative studies as explained in Chapter 4, section 4.3.4. Participants had provided written informed consent to participate in the quantitative study and they opted to take part in the qualitative study by stating confirming "willingness to participate in an interview" on their informed consent form (Appendix- B9). The participants were selected sequentially based on that response. Inclusion and exclusion criteria has been explained in Chapter 4, section 4.3.6. In addition to the previously mentioned criteria, for this study, participants who were fluent English speakers, were included.

5.3.3 Procedures

Participants completed an online questionnaire (Qualtrics, Provo, UT, USA, 2015*)* prior to the taking part in the quantitative studies and the interview. The questionnaire included demographic data and the patient-reported outcome measures: the Tegner Activity Scale (Tegner & Lysholm, 1985), Sports Confidence Scale (Ardern et al., 2012), KOOS (Roos et al., 1998), and SF-12 (Ware et al., 1996). The $KOOS_4$ was calculated as an average score of four sub-scales excluding function during daily activities due to a high ceiling effect for that sub-scale (Senorski et al. 2017).

Face-to-face individual interviews were held. Four of the interviews were conducted only by MK, while two interviewers (MK and GS, both females) were present for the remaining six interviews. GS is an established researcher within the field of musculoskeletal physiotherapy, in addition to also having extensive experience in rehabilitation of patients with ACLR. MK is the PhD candidate, with clinical experience in musculoskeletal rehabilitation.

All interviews were conducted in the School of Physiotherapy, lasting from 20 to 40 minutes. No interview was repeated. The interview guide had open-ended questions and was developed and refined by the research team via review and reflection after 2 to 3 interviews (Table 5.1). The interview guide was updated following discussion in the research team regarding the on-going interview process following 2-3 interviews. It was to reflect back on the process if there is any room for the improvement. Sequence of questions in the interview guide was changed by placing the open-ended questions in the start of the interview. While the guide provided some structure, the selection of specific questions and their respective order depended on how the interview proceeded. Field notes were made during and after the interview. Special phrases, words or expressions of the participants were noted down during the interview. It helped in the data analysis while generating the codes for the participants. The interviews were recorded with a digital audio-recorder (Sony R- IC Recorder) and transcribed verbatim.

Table 5.1. Interview guide

Section 1- General information about knee
1. Please could you give me some background information about yourself in terms of your occupation and sports background?
2. Please could you describe to me how your knee injury happened, and what happened with the knee since then?
3. How do you feel about your reconstructed knee at the moment?
Section 2- Level of sports and recreational activities
4. Please tell me more about your level of physical activities for recreational purposes and exercise in the past year?
a. Prompts: Do you think your reconstructed knee still influences the physical activity levels?
b. How does your current physical activity or sports compare to before injury?
c. If there are still differences in level of activity before and after the injury, can you explain why you have not returned to the same level?
d. Prompt: are there factors that make you feel more hesitant? If so, why do you feel hesitant or fear of re-injury during sport?
Section 3- Health-related quality of life
5. How would you describe your confidence in your knee during sports and recreational activities?
a. Prompts: How much are you troubled with lack of confidence in your knee?
6. How you modified your life style in terms of your sports, occupation and recreation to accommodate your reconstructed knee?
7. How do you think pain and other problems related to your knee interfere with your normal work?
8. In hindsight, what other choices may you have made in terms of surgery and rehabilitation?
9. In hindsight, what worked very well for you during surgery and rehabilitation?
a. What didn't worked well for you?
10. Overall, how is your knee health these days? What works well for you in terms of physical activities and sports and what does not?
Section 4- Recommendation and advice for ACLR participants
11. What are your concerns for future in terms of any activities related to your knee?
a. Prompts: Would you be able to maintain your current exercise level in future?
b. Expectations? Challenges?
c. Knee function? Activity level?
d. How likely are you to recommend the ACLR surgery to patients with ACL injury?
12. What will be your overall advice for people who had an ACLR?

5.3.4 Data analysis

The quantitative data were entered into the Microsoft Excel spreadsheet (Microsoft Office 2013) and descriptive analyses (median and ranges) were performed for the patient-reported outcome measures. Wilcoxon signed rank test (IBM SPSS 23) was performed for Tegner Activity Scale to compare the pre- and post-injury physical activity levels.

The General Inductive Method was used for the interview data (Thomas, 2006). This method allows to condense extensive and varied raw text data into a brief, summary format and also helps to establish clear links between the research objectives. Moreover, this method allows the analysis to be data driven. The transcriptions were read multiple times and text segments that reflected the participants' experience were identified and coded. The codes were categorised and the researchers developed links between these categories, identifying themes relevant for the research aims. After the primary analysis of the available data and when no new codes evolved from the next two interviews, it was deemed that data saturation had occurred (Baker, Edwards, & Doidge, 2012; Fugard & Potts, 2015). Data saturation was reached by the eighth participant and no further categories were added with the final two participants. Moreover, the participant sample consisted of the mixture of people with different ages and professions, indicating a rich data.

One researcher (MK) analysed all the interviews, while a second researcher (GS) analysed every second interview. The codes produced by the researchers were data-driven and were then compared, discussed and negotiated. The categories and emerging themes and sub-themes discussed and confirmed within the research team. The key themes were cross-referenced back to the original text to ensure that it was an accurate representation of the participants' perceptions of their experiences. Supporting quotes that most accurately reflected the key themes and sub-themes were selected. A summary of the results were sent to the participants for verification and feedback from the participants was synthesised into the final analysis. The interpretation of these combined findings is presented in the discussion section.

5.4 Results

Twelve participants were asked to participate in the study. Two of them chose not to take part in the study due to unknown reasons. Seven females and three males (median age 28.5 years, range 20-52 years) participated in the study. They had undergone ACLR at a median 6 years (range 3-10 years) previously and five of the participants had injured their left side. Four participants had patellar tendon graft, five had hamstring and one participant was operated using the allograft. Four of the participants were students while the remainder had sedentary occupations.

There was no statistically significant difference between pre- and post-injury level of physical activities, as defined by the Tegner Activity Scale (Wilcoxen Signed Ranks test p=0.37). Based on the Tegner Activity Scale, five participants had returned to their pre-injury level of sports participation, one had increased the level (pre-injury level 3; post-injury level 4), while for remaining four participants the level of participation had decreased by two or more scores (Table 5.2).

The KOOS-function daily living indicated that participants had good function with activities of daily living (median 99/100) yet still experienced knee-related symptoms (KOOS-Symptoms median 59/100), and impaired knee function during sports and recreational activities (KOOS-Sports and recreational activities median 84/100). The median $KOOS_4$ was 69/100 (Table 5.2). Overall, they scored low quality of life (KOOS-

Quality of life= 53/100; range from 19 to 75) (SF- PCS= 55.50, MCS: 44.80). Results from the Sports Confidence scale (Table 5.2) indicated that, as a group, the participants still had decreased confidence in their knee (41.5/80).

Table 5.2. Participant demographics and patent-reported outcomes.

Participant ID	Age (years)	Profession	Time since ACLR (years) /Side of injury/Type of graft	Ethnicity	Pre-injury Tegner Scores	Post-injury Tegner	KOOS-Pain	KOOS-Symptoms	KOOS-ADL function	KOOS Sports/recreation	KOOS QOL	$KOOS_4$	Confidence during sports	SF-12 PCS	SF-12 MCS
P1 (W)	30	Pharmacist	9 /Left, PT	Nz European	6	6	97	54	99	90	63	78	41	55.50	47.96
P2 (W)	37	Programme facilitator	10/Right, PT	Nz European	6	1	67	39	93	80	19	54	51	41.61	39.39
P3 (W)	47	Doctor	9/Right, allograft	Nz European	3	3	78	89	99	40	38	67	64	53.94	48.80
P4 (W)	20	Student	5/Right, HT	Nz European	9	9	97	61	100	90	69	81	37	55.19	48.68
P5 (M)	22	Student	3/Left, HT	Nz European	9	9	100	61	100	85	63	80	39	55.50	47.96
P6 (M)	52	School Principal	4/Left, HT	Nz European	3	4	94	57	99	70	56	73	47	56.72	40.72
P7 (W)	21	Student	5/Right, HT	Nz European	7	4	94	71	100	80	75	82	45	47.79	34.44
P8 (W)	27	Teaching Fellow	7/Left, PT	Maori, NZ European	9	7	72	46	94	50	44	56	52	47.79	51.97
P9 (W)	20	Student	3/Left, HT	Nz European	7	3	86	46	100	75	50	67	37	57.62	41.64
P10 (M)	34	Pharmacist	9/Right, PT	Sri Lankan	5	5	97	75	100	100	44	83	32	59.45	33.76
Median	28.5		6		6.5 (3-9)	5.1 (1-9)	94 (67-100)	59 (39-89)	99 (93-100)	80 (40-100)	53 (19-75)	69 (54-83)	41.5 (32-64)	55.50 (41.6-59.4)	44.80 (33.7-51.9)

Tegner activity scale: scale from 0 'sick leave or disability pension because of knee symptoms' to 10 'competitive sports – national or elite' (Tegner & Lysholm, 1985)

KOOS: Knee injury and Osteoarthritis Outcome Score: '0' indicates extreme knee problems and '*100' indicates no knee problems*, $KOOS_4$: average of Pain, Symptoms, function during sports and recreation, and quality of life., ADL: activities of daily living, QoL: Quality of Life, Confidence during sports: Scored out of 80, higher the scored lower is the fear of injury, Short form-12 Health Survey: Scores range from 0 to 100, where a zero score indicates the lowest level of health measured by the scales and 100 indicates the highest level of health, SF-12 PCS Physical component score, MCS: Mental component score, PT: Patellar tendon; HT: Hamstring tendon. M: Man, W: Woman.

From the interview data, sixteen categories were converged into three overlapping themes (Table 5.3). Among these themes two themes, 'Fear of re-injury versus confidence continuum' and 'Live life normally', answered our research aim. The third theme, 'need of reassurance and maintenance of the knee' was important to report as it explained the participants' knee-related concerns clearly. Themes and subthemes with supporting quotes are further described below. Ellipsis indicates an intentional omission of a word, or sentence from a text without altering its original meaning. Brackets indicate where additional words have been added into the sentence to clarify the meaning. Additional supporting quotes for the themes are shown in the Appendix-D2.

Focus of this study was to obtain the deeper understandings related to the participants' health concerns. Therefore, the quantitative and qualitative data were interpreted together. For instance, results from the Confidence During Sports scale indicated the presence of fear of injury in participants, the results of the interview data indicated the reasons for the persistence of fear of injury.

Table 5.3. Themes and subthemes from participant data.

Theme	Sub-themes	Categories
1. 'Fear of re-injury' versus 'confidence' continuum	Causes of fear of injury	Fear of experiencing the pain associated with the initial injury again
		Memory of inciting injury movement
		Long rehabilitation period and loss of muscle strength
		Impact of the injury and rehabilitation on family responsibility
	Behavioural manifestations of fear of injury	Concern about playing conditions
		Hesitation in sports during certain movements
		Use of brace during playing
	Confidence	The fluctuating confidence spectrum
		Positive attitude
2. Live life normally	Influence on life	Modified life style
		Change in priorities and attitudes towards physical activity
3. Need of reassurance and maintenance of knee health	Seeking health professional advice	Continuing daily struggles
		Participant specific concerns
		Graft-site related weakness
		Maintenance of the muscle strength
	Concern for long-term disabilities	Concern for future osteoarthritis and TKR

TKR: total knee replacement.

5.4.1 The 'fear of re-injury' versus 'confidence' continuum

Engagement with physical and sports activities appeared to be influenced by a continuum between fear of re-injury and confidence, irrespective of the time since surgery. Those with less fear of re-injury appeared to be playing at higher levels and had no major hesitations while playing. This theme had three sub-themes based on underlying causes, consequences of fear of re-injury and the fluctuating levels of confidence during sports (Table 5.3).

5.4.1.1 Causes of fear of re-injury

Reasons for fear of re-injury were related to the participants' specific experience with the injury, surgery and rehabilitation. It included participants' fear of experiencing the pain associated with the initial injury again, memory of the inciting injury movement, undergoing a long period of rehabilitation, and further loss of muscle strength. The injury and rehabilitation had impacted on family dynamics and commitments, and participants did not want to go through that experience again.

Two participants remembered experiencing intense pain when the ACL rupture occurred.

> "I remember just being in a lot of pain so I don't really want to have to feel it [again]." P4

The memory of the inciting injury movement lead to decreased confidence during those particular movements, preferring to avoid those individual-specific movements.

> "I wasn't doing anything different, like I've jumped that way 100 times before so it's just kind of ….a memory thing, I suppose, and like when I came back, one of the first games I played, I stopped real suddenly to stop myself from going offside and it kind of locked back on me and I just …freaked out a little bit […], it's not that I think it'll happen again, it's more like just a memory." P7

The process of rehabilitation and regaining lower limb muscle strength had been a challenge for two participants, and they did not want to go through the process again.

> "It's mostly the weakness that I've got on that side and… yeah the long-term, like ….. if I'm fit, then it's fine but I'm not always fit

> and yeah there's definitely weakness on that side and I don't want to have to repeat all the rehab and everything else again, 'cause it does take a while for it to feel normal." P1

The ACLR and rehabilitation had required a change in family responsibilities for one participant in terms of child care and sharing responsibilities with their partner. Another participant had to take greater day-to-day responsibility for her children. Both participants noted that they did not want to impose the inconvenience associated with the commitment for rehabilitation on their family again.

> "Main thing probably is the fear, because my husband works in Australia and I am here with kids so I can't afford to be injured because I got no family [close by], and will be really difficult […] if I re-injured my knee." P3

5.4.1.2 Behavioural manifestations of fear of injury

Participants appeared to be oscillating between fear of re-injury and confidence. While they were confident with certain movements, they had low confidence and high fear of re-injury during inciting movements they associated with the initial injury. The fear influenced execution of the movements, and thereby their sports performance. Fear of re-injury led to concern about the playing condition and hesitation with specific activities. For example, five participants expressed concern about wet, frosty or uneven playing surfaces as they felt this increased the chance of slipping and re-injuring their knee.

> "I hate playing on slippery, when it is wet. If we are playing outside I don't like playing it, it is unstable. Wet surfaces are pretty bad. Just the uneven surface makes me feel uncomfortable." P8

Six participants reported being hesitant during specific sports-related movements, particularly during turning and changing directions. Even the participants who were able to return to their pre-injury level of physical activities reported being unable to perform at maximum effort. The primary reason for being hesitant appeared to relate to the risk of re-injury. Four participants reported guarding the knee to protect from injury during the game, and one participant indicated pain avoidance.

> "I'm just a bit, I think twice when I'm doing a heavy pivotal movement on the right and on the left I will just do it without thinking. Obviously I, actually modified, meaning …… , I try to change it to my left if I could." P10

Fear of experiencing the pain associated with the initial injury, memory of inciting the injury movement, long rehabilitation period, loss of muscle strength and impact of injury and rehabilitation on family responsibility had led to the fear of reinjury in participants with ACLR. The results of this sub-theme are highlighted in Figure 5.1. This fear was reported by eight participants, leading to behavioural manifestation in participants such as their increased concern about the playground conditions, hesitation in sports during certain movements, use of brace while playing and the fluctuating confidence spectrum in sports.

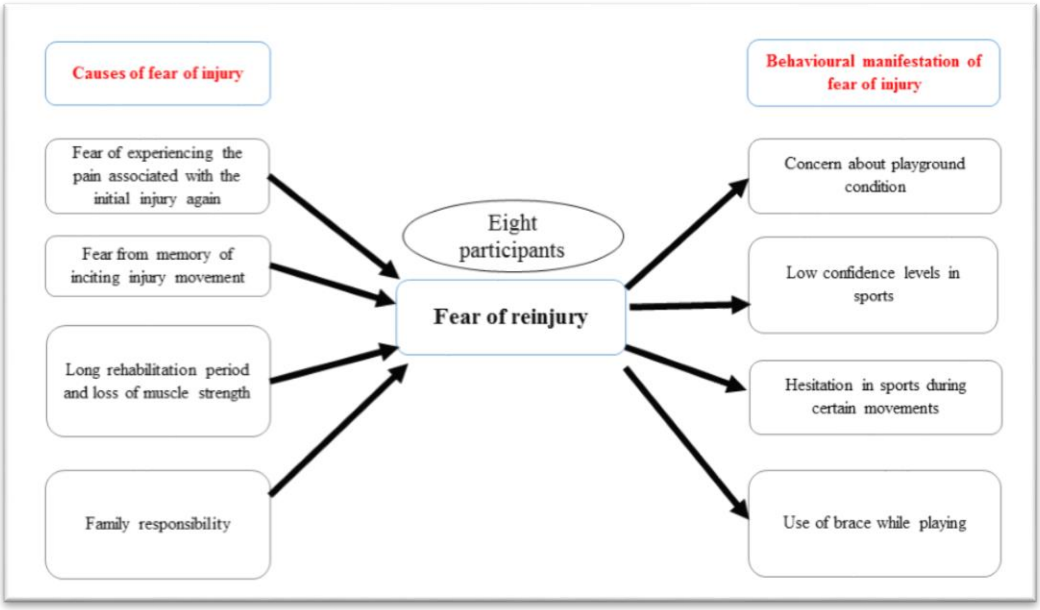


Figure 5.1. Causes fear of re-injury and its consequences (n=8).

5.4.1.3 Confidence

There was a spectrum of confidence levels among the participants, also reflected by the Confidence during Sports scale (range 32 to 64). Only three participants described themselves as having regained confidence in their injured knee. Two participants reported having lack of confidence during sports while one participant (3 years post-surgery) suggested his confidence was still steadily increasing, describing how continuing to train and playing soccer was contributing towards improved confidence.

> "I remember the way I was playing soccer at the start …, I was just tip toeing around, I wasn't really like trying to turn, I was real conscious of the way I was turning …… but then, throughout the football season I just learnt that I can actually manage all of those things….I think I am still….gaining confidence in it…." P5

One participant described himself as confident during sports but still cautious with specific knee-related activities. For some participants lack of confidence was not a problem.

> "But with the right conditions and knowing that my fitness is in the right place, then it doesn't hold me back." P1

A varying spectrum from low to high confidence levels was seen among the participants which may affect their overall performance. Those with low levels of confidence were unable to perform at maximum effort, and one participant also indicated loss of confidence in the contralateral uninjured knee.

> "I don't feel confident in that knee or either of them now though, so no it's not just the one that had the operation." P2

> "There is definitely times where I don't trust myself to run, well I don't trust myself to run or to sprint to be able to catch a ball or something so I will just jog because I don't have the confidence because both times that I have done it has been at a sprint so that is the time when I am the least confident." P8

On the other hand some participants no longer focussed on the knee while playing.

> "I'd say most of the time I don't think about it [the knee] too much." P1

Two participants used braces for their knee during sports to increase confidence, while one participant strapped the knee during weight training in the gym.

> "I do use a brace when I do snow skiing. I don't think it does anything but it just gives me a little bit more confidence or [...] knowing just to protect it as such." P9

A positive attitude played an important role in the overall outcome. Some participants re-gained trust in their knees, investing much effort to optimise results.

> "I know that it's never going to be as good as my left but I can live with that but I want to make sure I do everything possible to make that better. For some reason I think I'm actually stronger now than before." P10

However, others described their struggles with returning to sport.

> "I played in the team but I had to pull out of the team because.... I don't know if I didn't trust it or if my knee wasn't strong enough, but it wouldn't hold out with my head. I was almost protecting my knee in everything I did, so every time I jumped up I'd land on the other leg. I'd always turn on the other leg, and I was kind of just leaving the injured one behind, or the surgery one behind. Tried again in 2014 and then just decided I'd flag it and just do something else." P9

5.4.2 Live life normally

This theme describes the participants' overall approach to continue with life as normally as possible in terms of ADL, professional and social domains, though with modified life style strategies, priorities and attitude towards physical activity. None of the participants had to change their occupation or career plans due to their knee injury. However, a range of levels of recovery was apparent, with one participant describing the ACLR as having a deleterious effect on her life (P2, 10 years post-ACLR, $KOOS_4$: 54), while the other reported minimal effect of their injury to their current ADL, professional and social life (P10, 9 years post-ACLR, $KOOS_4$: 83).

The participants had adopted strategies to continue with an equivalent or increased level of physical activity, and often sought alternative solutions when knee symptoms affected movements or loading.

While most participants described being cautious, caring and mindful of the knee during physical activity, those with poor knee-related outcomes were more likely to express anxiety associated with avoidance of specific activities. Besides knee-related factors, changes due to family, occupation and other commitments also had influenced the participants' priorities for physical and sports activities.

> "I don't jump on the trampoline as much, I do it sometimes but I'm really conscious that it feels, in my head, I think it could go wrong very easily […]. I probably walk, like so I used to walk a lot and now I think if I walked to work, for example then how sore am I gonna be for the rest of the day or will my knee be able to cope then walking home, does that make sense 'cause…" P2

Three participants who had a Tegner score decrease of ≥ 3, described continuing to avoid 'high' risk activities, including those considered to be for fun:

> "….I'm not as adventurous anymore, how I used to be […]; I play the safe road now. [….] I've got older brothers and they're go go go, so I do pull back a bit and stay with mum sometimes now instead

> of going off with them. But other than that I still join in. I still go bike riding and skiing and everything." P9

It became apparent during the interviews that a fear of re-injury was contributing towards changed behaviour in terms of physical activity.

5.4.3 Need of reassurance and maintenance of knee health

Continued advice from health professionals regarding individual-specific needs related to the knee was suggested by six participants. Those who had been able to return to sports had different knee-related concerns than the less physically active participants. Continued daily struggles were still evident for some participants, while they also were aware of the need of long term maintenance of muscle strength, in particular for graft-related weakness.

Nine participants reported continuing to struggle with knee symptoms such as pain, stiffness, achiness, and pain after running. However, those problems did not always appear to limit their ADL or sports-related knee function.

> "Kneeling gets really uncomfortable. I can do it for a little bit, but I prefer to sit in a low squat than kneel... Pain will be minor and it is not…. too major but then sometimes it will be mainly, from after playing a game or training and it will just ache. Going upstairs is generally fine, it is the going down, if I am walking in bare feet, on like hard concrete it is not very good." P8

Apart from the daily struggles, three participants indicated their concerns related to running. Participants indicated their difficulties related to the changing directions while sprinting, or being conscious about the knee while running. One participant indicated her preferences for avoiding hard surfaces while running.

> "Yeah I don't like to [run on hard surface], well I do run on concrete a bit but I really prefer not to, just 'cause like I get a lot more pain,..a little bit more pain, not a lot but definitely the softer surfaces." P7

Those who had not been able to return to sports appeared to have different knee-related problems, for instance, problems related to pain after an extended amount of physical activity, and had an anxious attitude towards their knee.

> "I probably walk, like so I used to walk a lot and now I think if I walked to work, for example then how sore am I gonna be for the rest of the day or will my knee be able to cope then walking home…" P2

However, those who had successfully managed to return to sports highlighted graft site-related weakness as an issue. Graft site weakness was identified as a subcategory for seeking professional advice.

> "I pulled it [Hamstrings] about three times and then I just went, I had to sit out of football for about a month or two this season. P5

Participants understood that they continuously needed to maintain thigh muscle strength to decrease risk of re-injury and graft-related muscle strains. One participant (P6, KOOS4=73) indicated changes in daily behaviour specifically to maintain and increase knee-related physical performance, for example taking stairs instead of the lift.

> "At this stage I feel like I have …, got to keep, ….building or at least, maintain the leg strength, and I have learnt from earlier in the

> year I can't neglect the hamstrings especially because if I do, I think it makes [them].. susceptible, so, I better get working at that." P5

Muscle strength was perceived to be critical to manage fear of re-injury and improve confidence.

> "I think probably my fear of injury is less when I'm stronger ……so like the stronger I get, the less worried I am about injury and then I get weak again, I'm like oh it could go but I know that's not true 'cause it's a ligament, but it's just the feeling of being strong and knowing that you've got a lot of support around my knee, that would make me a lot more confident" P7.

Another participant suggested the need for a supervised exercise program which should decrease fear of re-injury.

> "I think maybe an exercise plan that challenges my head and lets me know that I can do these things. Maybe to know I've got the strength, like physically do a test or something and see that yes, you do have the strength to do these things. It's not going to give way. And then do the activities and realise that it's fine" P9

Participants, thus, indicated the need for on-going health professional advice to manage fear of injury and continuing exercises to improve muscle strength and movement control. For some participants, contact with their health professional provided re-assurance.

> "I need my Specialist to every so often to and have a check up and make sure my knees fine 'cause for me it really helps to reassurance from for example from the likes of Doctor XX. Because, …. I have a lot of faith in him and he's a Specialist in his area. So if he tells

me I'm doing the right thing then I know I'm doing the right thing."

P10

Six of the participants were concerned about long-term risk of knee osteoarthritis and pain, and one mentioned the possibility of future need for knee replacement.

> "I am aware that I might develop osteoarthritis in the knee and I just take it as it comes." P3

> " I'm just worried about when I get old, it's gonna be really sore but immediate future, no issues." P7

Overall, participants' perspectives can be summarised into negative and positive experiences based on the outcome of the surgery, as indicated by the themes and subthemes of the study results (Figure 5.2). Participants had adopted different strategies to adapt to the influences of injury on their lives. Negative experiences of the ACL injury and surgery appeared to have led to fear of injury, avoidance of specific activities, change in priorities towards the physical activities and minor struggles related to daily life which indicated the negative experience of the participants. Those with positive experiences were able to regain confidence during sports, return to preinjury level of sports, or even increase the level of physical activities compared to the preinjury level following the surgery. Participants with negative experiences appeared to have more anxiety and fear related to the future of the knee. In contrast, participants with positive experiences were 'mindful' and 'caring' towards their knee instead of worrying about the future of the knee. Changed priorities in terms of physical activity were evident in participants, both those with negative or positive outcomes. Those with negative experiences preferred activities associated with low levels of exertion (e.g. driving rather than walking). On the other hand, those with positive experiences, were more interested in engaging in physical activity (e.g. preferring to walk up the stairs rather than using the lift). They appeared to have focussed on all possible efforts to improve and maintain knee health.

Overall, participants are trying to live life normally, whether they had positive or negative experiences with surgery and rehabilitation. While participants with negative experiences are more influenced by the fear of injury and they avoid specific activities, those who were more confident are trying to live normally though are more careful or mindful during the sports or physical activities. Most of the participants suggested a need for access to health professional's advice in the long-term, either to improve their knee health, or for reassurance related to their knee, such as graft-site related weakness, minor pain and soreness in the knee and maintenance of the muscle strength.

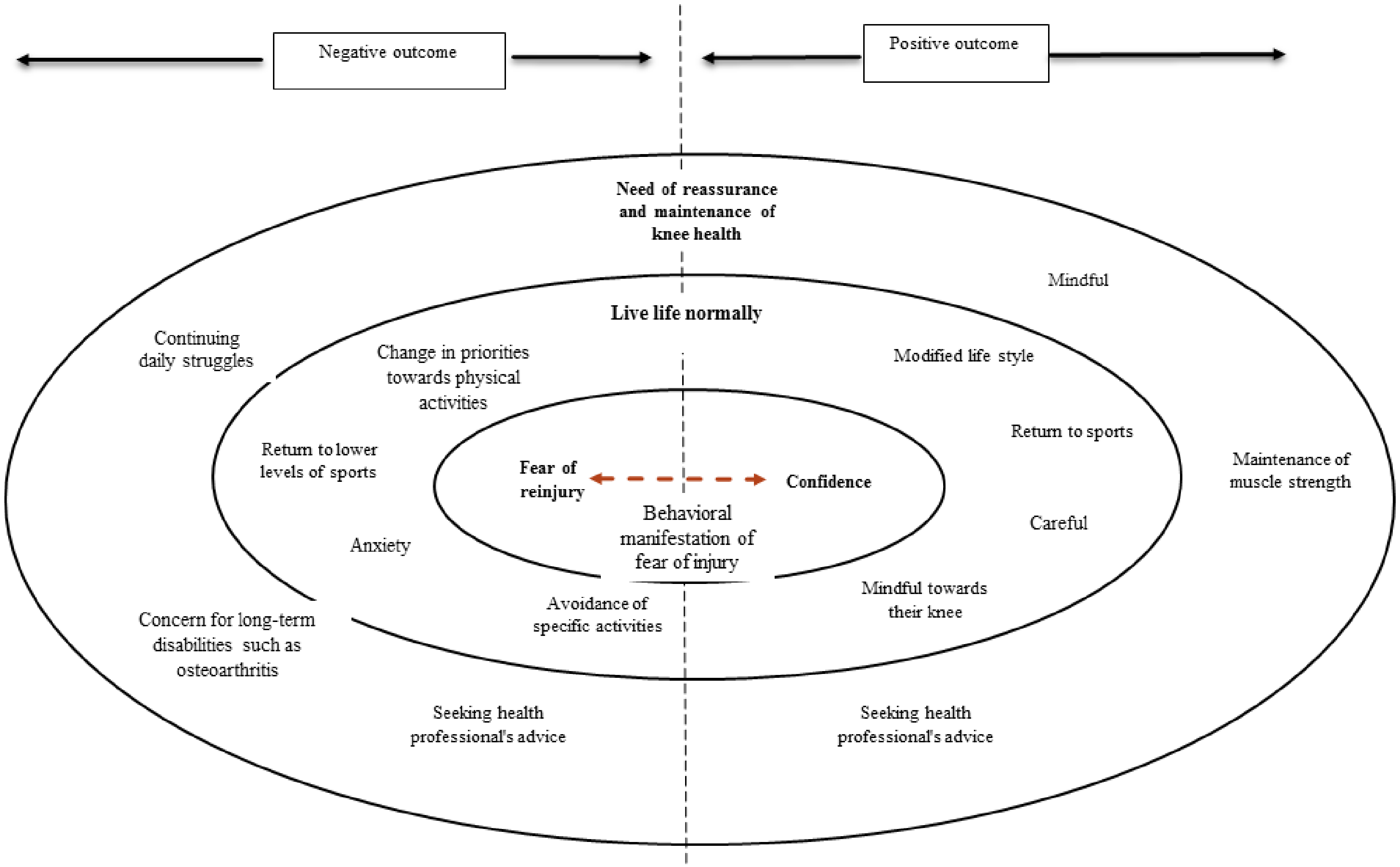


Figure 5.2. Concept of the three themes emanating from the analysis of the participant concern

The data was also reviewed in the ICF model to help to distinguish some of the areas where problems were noticed. It was found that participants had reduced levels of physical activity and participation in sports and recreational activities. From the results of Chapter 4, the impairments in body structure and function are already known.

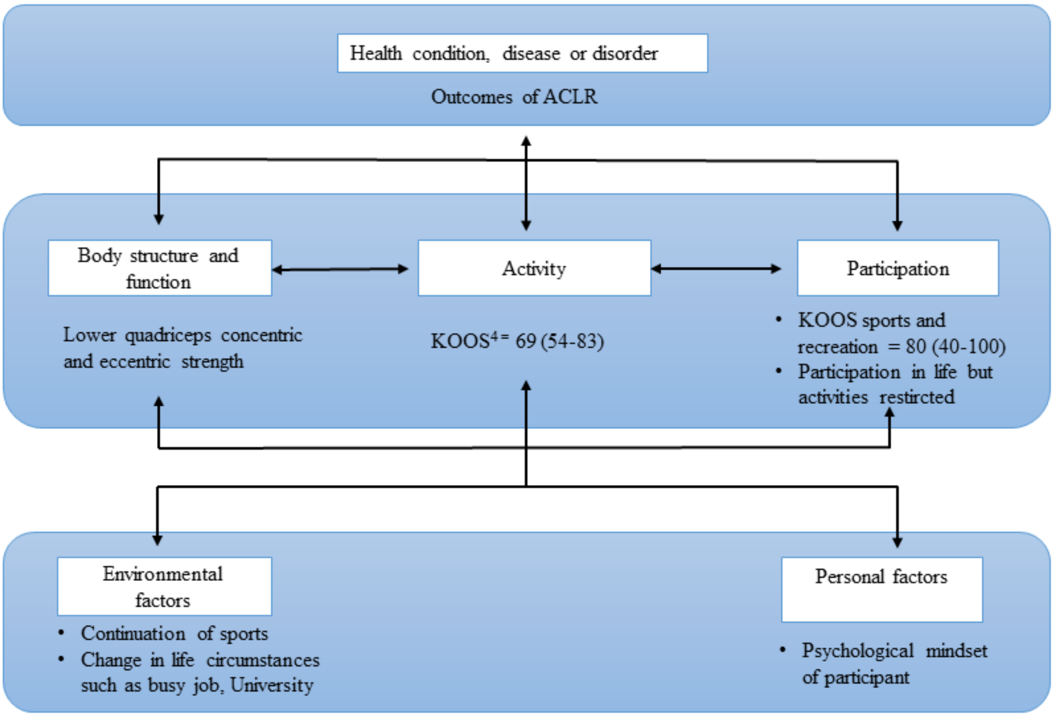


Figure 5.3 **ICF model based on the study results.**

5.5 Discussion

A previous study from our Centre with participants up to 3 years following ACLR indicated the significant impact ACL injury and the treatment had caused in their respective lives (Scott et al., 2017). The aim of the present study was to explore participants' experiences and perspectives about the outcomes of ACL injury and surgery in the long-term (2 to 10 years post-surgery) in relation to physical activity, sports, occupation and quality of life. The primary observation of the current study suggested that, as a group, participants did not have significant differences in the physical activity levels compared to the pre-injury levels and their ADL and professional lives were minimally affected. However, they continued to experience knee-related symptoms and had fluctuating levels of confidence during specific sports-related tasks.

As discussed in the previous Chapter (Chapter 4, Section 4.8) quality of life has been defined as the expectations of health versus actual experience (Carr et al., 2001), participants perceived their KOOS QOL as low (Table 5.2). It may be because of their relatively young age (median 28.5 years), and high health expectations from their health, thereby potentially contributing towards their low ratings of for the KOOS QOL scores. This cohort of participants reported better quality of life KOOS QOL than the larger cohort in Chapter 4 (Table 4.4), which may be due to the less experience of knee pain, symptoms and better function in activities of daily living and sports and recreation. Scores of KOOS QOL for this group of participants were similar to other studies exploring outcomes of ACLR but with older participants, averages of 37 and 45.6 years respectively (Meunier, Odensten, & Good, 2007; Tengman et al., 2014). The low KOOS-QOL scores of the current study were supported by the SF-12 scores. We found low scores for physical (median =55.50) and mental components (median = 44.80), suggesting that apart from the physical impairment, lowered mental health was also an important concern for participants with ACLR. The KOOS ADL scores indicated excellent recovery (99/100), however, the interview data indicated that participants still had minor daily struggles such as knee symptoms during stair negotiation, kneeling or running.

Our study results are similar to another study from Sweden, exploring the knee function at the median duration of 11.5 years in a cohort of 56 participants following surgery in Swedish population (Möller et al., 2009). Participants of that study had similar scores in KOOS pain (median=94), function in ADL (median=100), recreation (median-75) to that of our study results except from the quality of life scores (median=81). The differences may be due to higher age group (approximately 38) of participants in that study group compared to that of our study. Therefore, the differences in outcomes across various regions seems negligible.

Two main themes relating to the research question emanated from the interviews: 'fear of re-injury versus confidence continuum', and 'live life normally' (Figure 5.2, Table 5.3). Despite ACLR having been performed up to 10 years earlier, fear of re-injury was still present, irrespective of participants' level of physical activity. The fear of injury in the current study appeared to be primarily driven by negative experiences from ACL injury, surgery and the commitments the long post-surgical rehabilitation period had required and their role in the family commitments, which is in concordance with findings by (Ross, Clifford, & Louw, 2017). The fear influenced their return to play such that one participant was unable to return to pre-injury sport, changing to an alternative sports with less knee-related loading.

The current study showed that, while participants had continued with their lives "as normally" as they could, the re-injury fear persisted. They suggested that maintaining the physical activity and confidence in the knee would require vigilance for life in order to not to injure the knee again (Scott et al., 2017). Previous studies have shown that fear of re-injury was present between one and two years following surgery (Flanigan et al., 2013; Heijne et al., 2008), decreasing at around 3 years following surgery (Gignac et al., 2015). Our findings contrast with those by (Ardern et al., 2012), finding that participants playing sports on average 7 years following ACLR did so with low levels of fear. Those participants were regular recreational or competitive athletes before ACL injury and at the time of the study, which might have contributed to low levels of fear of injury (Ardern et al., 2012). On the contrary, we had a mixed cohort of participants and only some of them were the regular recreational athletes, which may explain why some of the participants of this study had less fear of injury than the others.

Findings of Chapter 4 indicated the muscle strength deficits on the injured side (Section, Table 4.3). In this study, two participants had explained their struggles with gaining the muscle strength in rehabilitation and a factor causing fear of re-injury in them. Participants also indicated the need of health professional to maintain the muscle strength in the long-term following surgery. Exercise protocol to improve the muscle strength can be prescribed to the patients by health professionals followed by patient-education regarding the strength maintenance exercise programme. Muscle strength deficits on the injured side seem to have wider implications on participants overall health, concerns and confidence, therefore, needs more attention in the rehabilitation and in later stages as well.

Competitive athletes potentially are more likely to have continued access to health care and support beyond the usual timeframes of immediate rehabilitation. On the other hand, our study included participants who, at the time of injury, were undertaking different levels of physical activity, ranging from highly competitive sports (Tegner Score 9, e.g. competitive soccer, rugby) to those who had low levels of knee-related activity (Tegner Score 3, swimming or walking) and had variable access to continued health care related to the knee. This may have contributed to the persistence of fear of injury in the current study, despite the duration following ACL injury being up to 10 years following surgery.

Despite minor daily struggles, participants were trying to continue their lives 'normally' with some modification in life style and priorities. They reported having had a change in the attitude towards their knee. Participants choose to consider the safety of their knee first while making the choices of activities. While some participants were more mindful of their knee in a positive, caring attitude, others had anxiety associated with it.

One of the participants indicated behaviour modification by taking stairs instead of lifts towards maintenance of knee-related health. In another study, participants from 5 to 20 years following surgery, who changed physical activity preferences and their lifestyle early after ACLR reported better quality of life (Filbay et al., 2016). Similar behaviour modification of overall physical activity and exercise may need to be considered. Behavioural cognitive therapy, including relaxation and imagery, has been used during the ACL rehabilitation and was reported to enhance psychological and physical aspects of recovery along with the, improved coping, and reduced re-injury anxiety (Cupal & Brewer, 2001). Gymnasts also have been reported to use strategies to overcome fear including thought-stopping "just go for it", imagery, self-talk, positive thoughts, selective focus and attention, and relaxation (Magyar & Chase, 1996). Similar strategies may be considered following ACLR to enhance self-management and self-efficacy in the long-term.

Besides concerns with daily struggles, fear of re-injury and fluctuating levels of self-confidence, the participants also discussed concerns about potential risk of future osteoarthritis. While health professionals should inform patients with ACLR of implications of such risk, the discussions should be within the context of providing individual-specific strategies to minimise such risk. The importance of considering psychosocial responses to ACL injury was highlighted in the previous study exploring patients' perspectives of surgery up to 3 years following surgery (Scott et al., 2017). In a parallel study, physiotherapists reported using a biopsychosocial approach as part of the care they provided towards rehabilitation of patients with ACLR (Von Aesch, Perry, & Sole, 2016), highlighting that they were aware of the need to address psychological and physical recovery during rehabilitation. However, they also perceived that they may need more formalised training in this field to optimise rehabilitation and patient outcomes in the long-term. Collectively, past studies and the current study highlight the importance of addressing the psychological and social needs of the patients during rehabilitation to minimise lingering symptoms and enhance self-efficacy in the long-term.

5.5.1 Methodological considerations

The quantitative data towards this research project was collected prior to the interviews, allowing the participants opportunity to meet the principle researcher for this study (MK), establishing rapport, prior to the interviews. The patients' perspectives about the influence of ACLR on their lives were in agreement with the results of patient-reported outcome measures especially about the Confidence during sports scale and KOOS (Teddlie & Tashakkori, 2009). Credibility of the results of this study was ensured by: (1) development of the interview guide by the research team through discussion and was updated following an initial 2-3 interviews; (2) the audio-recordings and verbatim transcriptions of the interview, open atmosphere during the interviews, the researchers bracketing prior experiences and thoughts, member checks of the study results (Appendix – D3)(Thomas, 2006); (3) peer debriefing of the overall results following the complete analysis of the transcriptions independently by three of the authors.

Trustworthiness and dependability of data was established by parallel coding of every alternative interview by a second researcher (GS) and by providing the additional quotes (Appendix- D2) (Thomas, 2006). All the interviews were face to face, employing the same method of data collection for all the participants, hence, decreasing the risk of bias which could be due to lack of visual cues and loss of informal communication and contextual information with the telephone interviews (Sweet, 2002).

Confirmability of the study findings were ensured by the open discussion among three of the authors following the analysis of the results. The results are valid experiences for the ten participants included in this study and most of the participants were from New Zealand, therefore, it is difficult to generalise the findings to different origins and countries.

5.6 Conclusion

Participants strove to "continue living life normally", with variable levels of current physical activity and involvement in sports. The ACL rupture appears to lead to long-term fear of injury and behavioural manifestations, with fluctuating levels of confidence during physical activity and sports. The participants, up to 10 years post ACLR, reported variable levels of knee-related quality of life based on the KOOS QOL scores. Participants were concerned about the future risk of re-injury or osteoarthritis. Health professionals should consider a long-term individual-specific maintenance programme to improve and maintain confidence and self-efficacy, and promote physical activity.

5.7 Summary

Participants continue to experience fear of re-injury and low confidence in the injured limb during sports-related movements. Different reasons for the persistence of fear of re-injury were found along with the consequences of this fear. Hesitancy during movements, experienced by some of the participants may be related to the less weight bearing on the injured side and shifting the joint loading on the contralateral side. These are important findings for the patients and clinicians as longer-term deficits such as lower loading on the injured side may be explained, in part, by those emotional responses.

Lower limb biomechanics on the injured limb along with the contralateral side of participants with ACLR were explored and compared to the uninjured control group in the next chapter (Chapter 6).

6 Knee biomechanics in participants with anterior cruciate ligament reconstruction compared to the Control group during stair navigation

6.1 Prelude to Chapter 6

Findings from the systematic review and meta-analysis (Chapter 3) indicated that knee angles were likely to recover fully by 6 years, on average, post-ACLR when comparing the injured side to the contralateral limb, and to a Control group. However, joint moments continue to be low when comparing the moments of the injured to the contralateral limbs up to an average of 6 years post-surgery, especially the external peak knee flexion and adduction moments. Together, the findings related to the joint moments indicate the need to explore whether the moments recover in the mid- to long-term following the surgery. In this chapter, differences in the knee angles and moments in the injured limb were compared to the contralateral limb in participants with ACLR from 2 to 10 years following surgery, and to a Control group, during stair ascent and descent. The results of this study point to moment symmetry being compromised in the long-term following surgery in participants with ACLR.

Chapter 6

6.2 Background

Differences in biomechanical variables such as knee flexion and adduction moments appear to be important when comparing the injured side with the contralateral uninjured side in participants with ACLR and with uninjured Control groups (Chapter 3, Figure 3.6 and 3.7). Lower flexion and adduction moments were present on the injured side in participants with ACLR from 22 to 26 months following surgery (Zabala et al., 2013). Similarly, knee flexion and adduction moments were lower on the injured side in participants with ACLR compared to the contralateral side and the Control group from 2 to 18 years following surgery (Hall et al., 2012). Altered joint angles and moments during ambulatory activities following ACL injury and reconstruction may contribute to the development of post-traumatic osteoarthritis (Foroughi et al., 2009; Nigg et al., 2000; Pietrosimone et al., 2017). A recent study has indicated that the external flexion moment is a contributor to medial compartment joint loading, therefore, analysing both flexion and adduction moment can provide deeper insight into the mechanics of joint loading (Manal, Gardinier, Snyder-Mackler, & Buchanan, 2013; Walter, D'Lima, Colwell, & Fregly, 2010).

Based on the results presented in Chapter 3, inspection of the forest plots (Chapter 3, Figure 3.7, Subsection 7.1.1) suggested a possible increase in the adduction moments with time following surgery. Previous studies have explored the moments early following surgery (less than 3 years) (Karimi et al., 2013; Webster & Feller, 2012a; Zabala et al., 2013), or have included participants with wide range of time following surgery (Hall et al., 2012), which could have diluted the results in the study regarding the magnitude of moments. The current study recruited the participants from 2-10 years post-surgery to explore if moments recover in the long-term.

The findings of the systematic review (Chapter 3)(Kaur, Ribeiro, Theis, Webster, & Sole, 2016) and other reviews were inconclusive regarding the magnitude of rotation moment and angles (Hart, Culvenor, et al., 2015). Lower internal rotation moments were present on the injured side compared to the contralateral knees of the ACLR group during stair ascent (second peak) and descent (second peak) (Zabala et al., 2013). Higher internal rotation moments are associated with mild to moderate knee osteoarthritis (Astephen, Deluzio, Caldwell, Dunbar, & Hubley-Kozey, 2008). Participants with ACL rupture have a higher risk of developing knee osteoarthritis (Lohmander et al., 2007). So the question is raised as to whether internal rotation moments might increase over time in individuals following ACLR, which may then become an indicator for knee osteoarthritis risk.

Asymmetry in moments and angles was present such that peak external moments were lower on the injured side compared to the contralateral side 8 months following surgery during drop vertical jump (Schmitt et al., 2015). These asymmetries may persist up to 2 years, or longer, following surgery (Paterno et al., 2007) and can be a risk factor for joint re-injury (Paterno et al., 2010). It is important to explore if the moment asymmetries persist in the long-term following ACLR. Moment asymmetries indicate altered loading and it may predisposes the individual to the risk of re-injury or early onset of knee osteoarthritis (Khandha et al., 2016). Asymmetries for knee moments were more apparent during stair ascent and descent compared to walking, as described in Chapter 3 (Figure 3.6 and 3.7). Therefore, this study was designed to explore the knee moments and angles during stair ascent and descent. The primary aim of this study was to assess differences in knee kinematics and moments between (1) the injured knee and contralateral knee in participants with ACLR; and (2) the injured knee in participants with ACLR and age-matched uninjured controls, during stair ascent and descent.

6.2.1 Hypothesis

1) The injured knees in the ACLR group will exhibit lower flexion and adduction moments and angles compared to the contralateral uninjured knees during stair ascent and descent.
2) ACLR group will have lower knee flexion moments and higher knee adduction and internal rotation moments during stair ascent and descent compared to the Control group.

6.3 Methods

6.3.1 Study design

This was a cross-sectional study, assessing differences in knee joint angles and moments in the ACL reconstructed knees compared to the contralateral uninjured knees and the uninjured Control group. The study design, study setting, ethic approval and participant recruitment were described in Chapter 4, section 6.3.5.1.

6.3.2 Equipment

6.3.2.1 Three-dimensional motion analysis system

To monitor lower-limb and pelvic movements during the stair ascent and descent tasks, a three-dimensional motion analysis system (Motion Analysis Corporation, Cortex 5.5 Santa Rosa, CA, USA) with 11 infra-red cameras, sampled at 150 Hz was used. The laboratory set up and positioning of the cameras has been shown in Figure 6.1. One floor-mounted force platform, AMTI force plate (AMTI Inc., Newton, MA, USA) sampled at 1,050 Hz, was used to measure the ground reaction force. The stairs consisted of two steps such that step 1 (step height: 20.5 cm; tread width: 37.5 cm) was placed directly on the force plate, which was embedded inside the floor. This step had a steel frame and was stabilised on the force plate by an additional 10 kg weight (Figure 6.2). The step 2 dimensions consisted of step height 93 cm and tread 152 cm. There was no direct physical contact between step 1 and step 2 and treads from the steps 1 and 2 were independent and completely isolated from one another (Trinler et al., 2016). There were no handrails on the sides of the stairs.

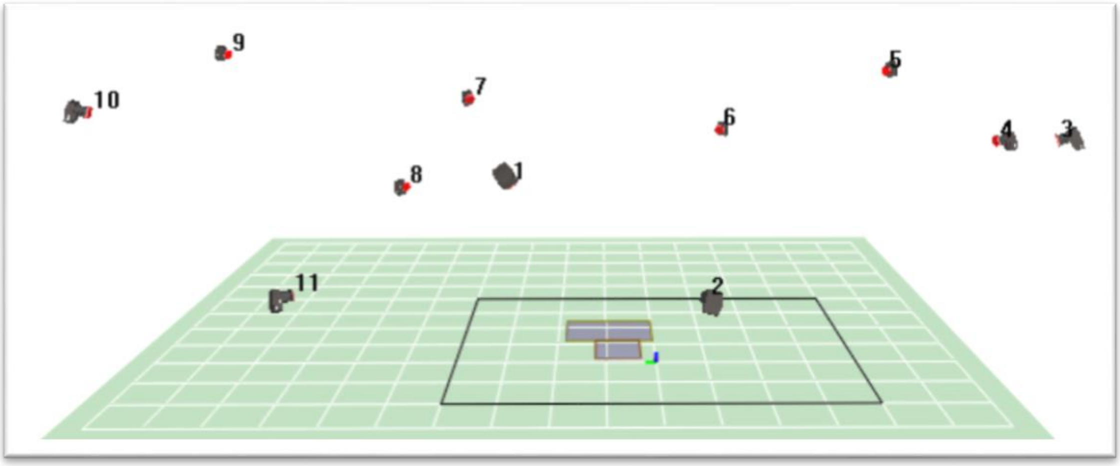


Figure 6.1 Camera set up for the motion capture, black outline near the force plate represents the capture volume.

Figure 6.2. Stair case used for data collection. Step 1 was placed over the force platform.

6.3.3 Procedures

A STROBE statement was used for reporting this study (Von Elm et al., 2014). Guidelines by (Stebbins et al., 2015) were also used for reporting of the gait-related methods and results.

6.3.3.1 Familiarisation with the lab and demonstration of the task

The participants were familiarised with the laboratory environment and with the tasks. The task of stair ascent and descent was demonstrated to the participants by the student researcher (MK). They were asked to repeat the stair ascent and descent tasks at least twice, leading with each side respectively, or until they were confident with the movement.

6.3.3.2 Demographic data and participant preparation

Participants' height and weight were measured. The participants were then prepared for the data collection and were asked to dress in a singlet, a pair of shorts and their own sport shoes. A set 43 reflective markers (diameter 12.5 mm) were placed on the skin with double-sided tape on the following landmarks of both legs and the trunk: over the first and fifth metatarsal heads on the shoe, calcaneus, medial and lateral malleolus, anterior and posterior of middle of the leg and thigh, two (superior and lateral) on the lateral leg and thigh respectively, medial and lateral knee joint line, greater trochanter, anterior superior iliac spine, posterior superior iliac spine, iliac crest, acromion-clavicular joint; L5, C7, sternum notch (Figure 6.3). Landmarks on both legs and trunk were identified using manual palpation. One researcher (student researcher) placed the markers on all participants to minimize between-researcher variability. Two research supervisors sporadically attended data collection sessions to ensure that consistency in methods was maintained. A research assistant was present at all times during data collection to assist with the participant preparation and execution of procedures.

Figure 6.3. Marker set: front and side view

6.3.3.3 Order of tasks

The order of the tasks consisted of static trials followed by dynamic trials. Participants were asked to stand still for at least 7 seconds for the static trial, which was used to obtain a reference point for the markers in quiet standing. Following the static trials, participants were asked to perform dynamic trials which were used for calculating the functional hip joint centres. Dynamic trials consisted of participants in single-leg standing; performing hip flexion and extension, abduction and adduction, and circumduction movement with the non-weight bearing leg. Each movement was performed twice. The student researcher first demonstrated the hip movements to each participant, after which participants practiced the movements. The participants were asked to perform these movements in a smooth, continuous motion while maintaining balance and minimising trunk movements.

6.3.3.4 *Stair ascent and descent*

All participants were instructed and encouraged to perform the stair ascent and descent in a natural manner and at their preferred speed. They performed five trials of stair ascent and descent for each side and were instructed which leg (left or right) should lead the respective trials. The participants were asked to start the trial on the verbal command 'go' given by the student researcher. For ascent, the participant started from a position relative to the steps and stepped forward with one leg and placed the contralateral foot naturally on Step 1, which was placed on the force platform (Figure 6.4). For stair descent, participant started from the second step and descended down with the leg to be tested onto the lower step placed on the force plate (Figure 6.5), and continued forward for two steps. Trials were randomised for all the participants to start between the affected and non-affected leg in the ACLR group, and dominant and non-dominant leg in the Control group. Performance for the stair ascent/descent were also videotaped with a digital recorder to monitor the procedure. These were only used if the researchers needed to check the side of movement during the data processing. The videos were not used for any other purpose.

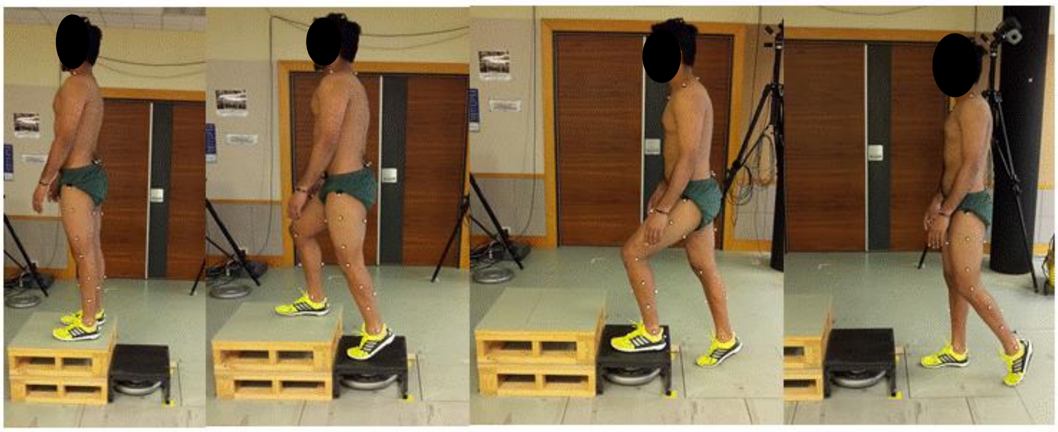


Figure 6.4. Stair ascent (from right to left) (1) starting position (2) foot on step 1, (3) foot on step 1 continue (4) finishing position.

Participants started one step length away from the stairs. In this photo, data of the left side during stance on Step 1 is being captured.

Figure 6.5. Stair descent (from left to right) (1) starting position; (2) foot on step 1, (3) foot on step 1 continue (4) finishing position.

Participants started from the second step. In this photo, data of the right side during stance on step 1 was analysed.

6.3.4 Data processing and analysis

6.3.4.1 Three-dimensional motion analysis

The motion capture system was calibrated according to the user guidelines using the L-calibration and T-wand. The motion capture system and floor-mounted force plate were synchronized with the Cortex software to define joint coordinate systems. The gain was 2000. The computer software (Cortex 5.5) was used to digitise the markers, and the kinematics (joint angles) and kinetics (moments) data were processed with Visual 3-D (C-Motion Inc, USA). Noise was reduced in kinematic and kinetic data using a third order low pass Butterworth filter with a cut-off frequency of 15 Hz. For the biomechanical model, the hip joint, centre were functionally estimated (Cappozzo, 1984; Leardini et al., 1999) while for the knee and ankle, anatomical joint centres were used (Wu et al., 2002).

6.3.4.2 Coordinate systems

Cartesian coordinate systems, global and local coordinate systems were used to quantify the movements. The global coordinate system was defined as the Y axis from antero-posterior axis, X- axis as the medio-lateral axis, and the Z-axis was defined as the vertical axis. A local coordinate system was defined using pelvis, thigh and tibia shank so that joint centre and axis of rotation could be defined (Figure 6.6). The pelvis, thigh, tibial and foot joint coordinate system were defined according to International Society of Biomechanics guidelines (Wu et al., 2002). The joint coordinate system is shown in figure 6.6.

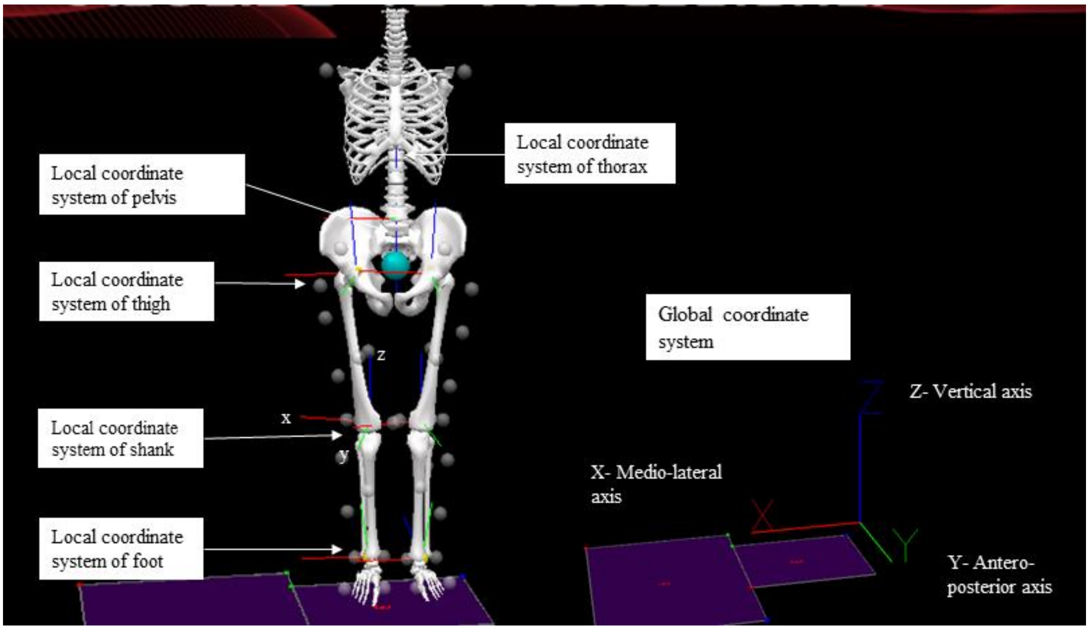


Figure 6.6. Global and local coordinate system

6.3.4.3 Kinematic events

Knee joint angles were defined as the rotation of the shank relative to thigh using the Cardan X–Y–Z convention where X represents flexion–extension, Y represents abduction–adduction and Z represents internal–external rotation (Ronsky & Yeadon, 1993). The stance phase (with the foot on Step 1) was defined from initial foot contact and toe-off. Initial foot contact (heel strike) was defined as the first time point when the force vector appeared from the force plate. Toe-off was defined as the time when the force vector disappeared. Swing phase was from toe-off and ended with that foot making contact with the floor. During stair descent, two phases of gait were considered for analysis: weight acceptance and propulsion (McFadyen & Winter, 1988; Sole, Tengman, Grip, & Häger, 2016). Weight acceptance of the leading leg was defined as the phase from heel strike of that leg on the first step to toe-off of the trailing leg on the starting step. Propulsion of the leading leg was defined as the toe-off of the leading leg to the toe-off of the trialing leg. All events were identified by the automatic algorithm (Visual 3D, (C-Motion Inc, USA) (Appendix-E1). All events were then visually inspected during the process and manually corrected if needed. All stride events were set and data extracted prior to expressing the events as percentage of the stance phase of the gait cycle. Kinetics, kinematics, and speed were averaged across the five trials for each side.

During stair ascent, the following outcomes were extracted: peak flexion and extension angles; peak knee adduction and abduction; peak tibial internal and external rotation angles. During stair descent, the following variables were extracted for weight acceptance and propulsion phase: peak knee flexion and extension, peak knee abduction and adduction, peak internal and external rotation. Table 6.2 includes the list of all variables. All stride events were set and data extracted prior to expressing the events as percentage of the gait cycle.

6.3.4.4 Kinetics

External joint moments were calculated through inverse dynamics (TP Andriacchi & Strickland, 1985). To account for variability between participants, moments were normalised to %BWxHt (Moisio, Sumner, Shott, & Hurwitz, 2003). The maximum and minimum knee moments in the three planes were used for analysis during stair ascent. For stair descent, the peak variables were calculated during the *weight acceptance* and *propulsion phase*. This resulted in two values of peak moments (1st and 2nd half of stance) for each of the three moments and each activity per knee. Knee extension, abduction and internal rotation moments were defined as positive peaks (peak 1 and 2) (Table 6.1).

Table 6.1. Joint angles and moments

Positive joint angles	Positive joint moments
Extension	Extension
Adduction	Adduction
Internal rotation	Internal rotation

6.3.4.5 Spatiotemporal variables

For each trial, the following parameters were calculated: stance time, stride time, stance fraction (stance time / stride time), stride speed, velocity of walking, and the time to peak adduction moment. The stance time was calculated from heel strike to toe-off. The stride time was calculated from toe-off to toe-off including the phase of heel strike. The time to the first peak adduction moment was calculated as a fraction of stride time (time to peak/ stride time).

Table 6.2. Outcome measures

Spatiotemporal variables	Kinematics (angles, degrees)	Kinetics (External moments) (Nm/kg.m)
Stance time (seconds)	**Stair ascent**	**Stair ascent**
Stride time (seconds)	Peak adduction/abduction	Peak adduction moment 1 and 2
Stance fraction (seconds)	Peak flexion/extension	Peak flexion/Extension moment
Stride speed (meters/second)	Peak tibial internal/external rotation	Peak internal /External rotation moment
Time to peak adduction moment (seconds)		
Fraction time to peak adduction moment 1 (seconds)	**Stair descent**	**Stair descent**
	Weight acceptance: Peak abduction/adduction	Peak adduction moment 1 and 2
	Peak flexion/extension	Peak flexion 1 and 2
	Peak internal /external rotation	Peak internal rotation 1 and 2
	Propulsion phase: Peak flexion/extension	
	Peak abduction/adduction	
	Peak internal /external rotation	

6.3.5 Statistical analysis

6.3.5.1 Sample size estimation

The sample size was estimated using the software GPower 3.1 (Faul, Erdfelder, Lang, & Buchner, 2007). The meta-analysis described in Chapter 3 reported an effect size of 0.38 for differences in knee adduction moments between injured and contralateral limbs during stair descent. The sample size for this study was estimated assuming an effect size of 0.38, an alpha set at 0.05 and power set at 0.80. Based on these values, the required sample size was 26 participants for each group, when conducting between- and within-group comparisons. Thus, a sample of 26 injured and 26 age-, gender-, and physical activity level-matched controls were recruited.

6.3.5.2 Kinematics and kinetics

SPSS Version 23 (IBM SPSS Statistics) was used for statistical analysis. Data from the ACLR group of the injured side were pooled together. For Control groups, the left and right sides were randomly assigned to “Side 1” and “Side 2” using an online software (Urbaniak & Plous, 2013) to have the same ratio as for the ACLR group in terms of right/left sides. Normality of the data was tested with histograms and Normal Q-Q plots. Data were found to be normally distributed with the data points close to the diagonal line in the Normal Q-Q plots. The normalised data (as a percentage of the stance phase) were exported from Visual 3D to MATLAB R2016a (The Mathworks Inc., Natick, MA) to create linear envelopes (means and SD) for the injured and contralateral sides of the ACLR group and the averages of Side 1 of the Control group (Appendix-E2).

Repeated measures analysis of variance (ANOVA) (2 x 2) were used to determine whether significant differences between-group (ACLR versus Control group) and side effects (injured versus uninjured sides for ACLR group, and Side 1 and Side 2 for the Control group) or interactions existed ($p>0.05$) between ACLR and Control group. Mauchly's test was used to test the assumption of Sphericity. Pairwise post-hoc tests were performed if significant group or side effects or interactions (group x sides) were found. Bonferroni test was used for the pair-wise comparisons. The Bonferroni method is considered to be a robust method and able to control alpha levels and reduces the chances of Type 1 error (Field, 2009). Effect sizes (Cohen's d) were calculated for significant differences and categorized as small (b0.5), medium (≥0.5 and b0.8) or large (≥0.8) (Cohen, 1988).

6.3.5.3 Repeatability of knee flexion and adduction moments

Trial-to-trial reliability and variability for assessing the peak flexion and adduction moments during stair ascent and descent were performed using the data of 12 ACLR and 12 Control participants. Intraclass Correlation Coefficient (ICC (95%, CI)) and Standard Error of Measurement (SEM) were calculated. Absolute values were reported for the ICC. The SEM was calculated by extracting the square root of the error mean square term from the ANOVA test (Weir, 2005). This method has the advantage of estimating the SEM independently from the ICC magnitude (Weir, 2005). The ICC's were classified as ≥0.7: high consistency/low variability, 0.5-0.69: moderate consistency/variability and <0.5: low consistency/high variability (Munro, 2005).

6.4 Results

Twenty-five participants with unilateral ACLR and 24 uninjured age- and gender-matched participants took part in the study. The characteristics of participants are presented in Table 6.3. The BMI of the ACLR participants were significantly higher than the controls ($p<0.001$, Table 6.3). Participant data related to the Surgery and rehabilitation provided by ACC and participants has been presented in Appendix- C7. Time between injury and surgery was calculated from the available data from ACC for 18 participants with ACLR (Appendix –C9).

Table 6.3 Participant characteristics

	ACLR	Control	p-value
Male/female (n)	25 (13W)	24 (13W)	
Age (years)	30.8 (9.7)	31.4 (10)	0.829
BMI (kg/m^2)	26.6 (3.6)	22.7 (3.6)	**<0.001**
Injured side	18 left/7 right	_	
Limb dominancy	22 Right dominant	23 Right dominant	
Time since ACLR (years)	4.7 (1.8) (range 2-10)	_	
Time between injury and surgery (months)	9.7	_	

n= Number, W= Women, ACLR= Anterior cruciate ligament reconstruction, BMI= Body mass index,

While the main aims of this study relate to knee moments, the spatiotemporal variables are presented first as descriptors of gait for the groups, followed by the kinematics, and finally, the moments.

6.4.1 Stair ascent

6.4.1.1 Spatiotemporal variables

There were no significant group or side effects or group x side interactions for spatiotemporal variables during stair ascent (Table 6.4).

6.4.1.2 Joint angles

Following initial foot contact, the knee moved from a position of approximately 50° flexion to extension during stair ascent (Figure 6.7). In the frontal plane and transverse planes, the mean abduction and adduction (valgus/varus alignment) and internal and external rotation angles remained below 5°. Standard deviations clouds appear to be large relative to the course of the means of the angles in the frontal and transverse planes.

In the sagittal plane, significant group effects were found for peak knee flexion angle between the ACLR and Control group (p=0.022) (Table 6.4) (Figure 6.7). Post-hoc pairwise comparisons found less flexion for the injured side compared to the side 1 of the Control group (mean difference 4.5°, 95%CI 1.8-7.1, p=0.001) (Table 6.5) while no significant difference was found when comparing the uninjured side of the ACLR group to Side 2 of the controls. Significant differences were present in the ACLR group between injured and contralateral side (mean difference 2.3°, 95%CI 0.80-3.80, p=0.003).

There were significant group x side interactions for peak flexion (p=0.004) and flexion-extension excursion (p=0.004). Post-hoc pairwise comparisons reported lower flexion-extension excursion angles (total range from peak extension to peak flexion) on the injured side compared to the side 1 of the Control group (mean difference 4.0°, 95%CI 1.12-6.72, p=0.007). However, no differences were found for the flexion extension excursion angles when comparing the contralateral side (ACLR) to Side 2 (controls) (mean difference 0.51°, 95%CI 2.80-3.82, p=0.755). No significant differences were present among the injured and contralateral sides in the ACLR group (mean difference 2.1°, 95%CI 0.57-3.74, p=0.009).

No significant group, side effects or group x side interaction effects were found for the frontal and transverse plane angles (Table 6.4). The analysis of the discrete variables in the frontal planes appeared to have greater knee adduction angles on the injured and uninjured sides of the ACLR group compared to the Control group (Figure 6.7). However, the statistical analysis found no significant differences between the groups (Table 6.4).

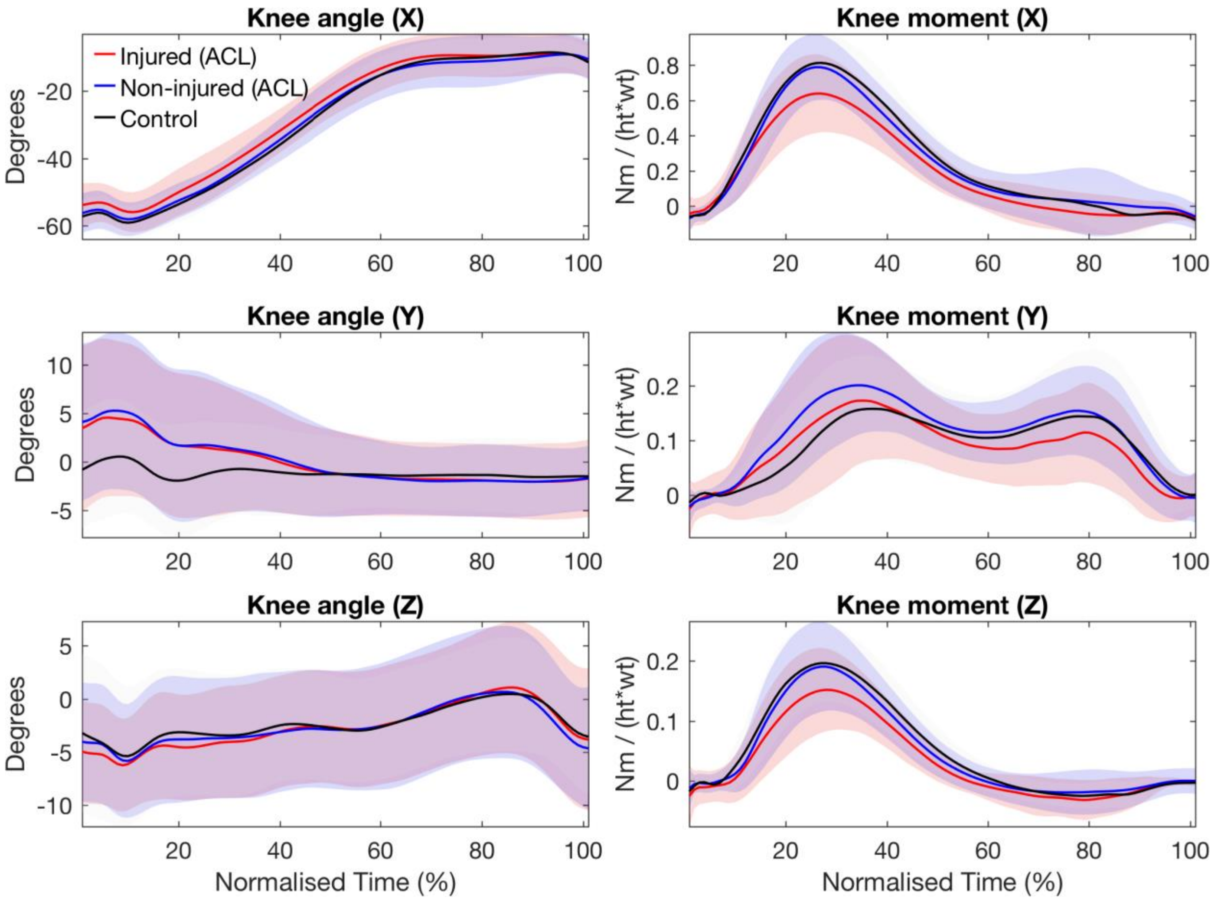


Figure 6.7 Linear envelopes (means and SDs) for angles and moments during the stance phase of stair ascent in participants with ACLR.

SD clouds are provided for the injured side (red) and contralateral sides (blue) of the ACLR group. Positive values indicate knee extension angle, knee adduction angle and internal rotation angle. Positive moments include knee flexion moment, adduction moment and internal rotation moments. Black line for controls indicate movement pattern of Side 1 of Control group. 100% for the normalised time refers to the stance phase during stair ascent. X-axis defines angles and moments in sagittal plane, Y- axis defines angles and moments in frontal plane, and Z- axis defines angles and moments in transverse plane.

6.4.1.3 Moments

During stair ascent, the knee generates an external flexion moment during the weight acceptance phase, followed by an extension moment during the propulsion phase (Figure 6.7). Two peak adduction moments are seen, one during each of the two phases of stance. During the acceptance phase, an internal rotation moment occurs, followed by an external rotation moment during the propulsion phase. Inspection of the linear envelopes (Figure 6.7) indicates that external knee flexion moments and the internal rotation moments were lower on the injured side compared to the contralateral limb and to the Control group. The knee adduction moment 1 may be higher on the contralateral limb compared to the injured limb in the ACLR group.

Statistical analysis of the discrete variables found no significant group effects for any of the peak moments during stair ascent (Table 6.4). Significant side-to-side effects were found for peak flexion (Figure 6.8) and extension moments. Significant group x side interactions were found for flexion moments ($p<0.001$). Post-hoc pairwise comparisons indicated lower flexion moment (mean difference 0.41, 95%CI 0.21-0.61, $p<0.001$) and significantly higher peak extension moments (mean difference 0.15 95%CI 0.01-0.28, $p=0.026$) for the injured side compared to the contralateral limb for the ACLR group. The difference for knee flexion moments between Side 1 and Side 2 of the Control group was not statistically significant ($p=0.380$).

The ACLR injured sides also had significantly lower flexion moments compared to the Side 1 of the Control group (mean difference 0.38 95%CI 0.12-0.64, $p=0.005$). A comparison between Side 1 and Side 2 of the controls revealed no differences in flexion and extension moments. The comparison of the uninjured side in the ACLR group with Side 2 of the Control group indicated no difference in flexion moment ($p=0.331$).

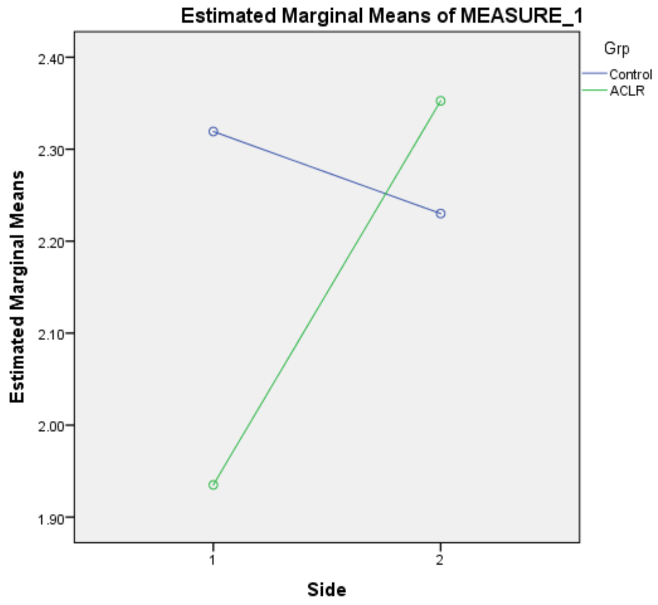


Figure 6.8 Diagram indicating the flexion moment asymmetry in participants with ACLR.

The contralateral (uninjured) sides (Side 2) of the ACLR group were generating higher moments compared to the injured sides (Side 1).

Table 6.4. Mean (SD) of spatiotemporal variables, moments and angles: stair ascent

	ACLR group		Control group				
	Injured side	**Uninjured side**	**Side 1**	**Side 2**	**Group effect**	**Side effect**	**Group x side interaction**
Spatiotemporal variables (n, ACLR=25, Control=24)							
Stance time (seconds)	0.94 (0.9)	0.95 (0.1)	0.91 (0.9)	0.91 (0.1)	0.255	0.541	0.526
Stance fraction (seconds)	0.64 (0.2)	0.65 (0.2)	0.65 (0.4)	0.65 (0.2)	0.466	0.820	0.091
Stride time (seconds)	1.43 (0.1)	1.45 (0.1)	1.43 (0.1)	1.4 (0.1)	0.515	0.924	0.773
Stride speed (meters/second)	0.68 (0.05)	0.68 (0.06)	0.69 (0.06)	0.69 (0.07)	0.599	0.821	0.986
Time to peak adduction moment (seconds)	0.32 (0.07)	0.30 (0.06)	0.32 (0.06)	0.31 (0.06)	0.809	0.118	0.406
Kinematics (angles; degrees) (n, ACLR=25, Control=24)							
Flexion	-55.6 (4.9) ∞*****	-57.7 (4.4)	-60.0 (4.2) ∞*****	-59.2 (5.0)	**0.022**∞	0.185	**0.004***
Extension	-6.3 (4.3)	-6.4 (4.2)	-6.9 (4.0)	-7.2 (4.8)	0.547	0.658	0.837
Flexion-extension excursion	49.3 (4.9) *	51.5 (5.9)	53.2 (4.9) *	52.0 (5.6)	0.124	0.427	**0.004***
Abduction	-3.8 (5.2)	-4.5 (4.1)	-5.0 (5.0)	-4.6 (6.0)	0.616	0.843	0.383
Adduction	4.8 (6.6)	5.3 (7.3)	3.7 (5.2)	3.5 (5.2)	0.347	0.896	0.656
External rotation	-7.4 (5.4)	-8.1 (6.1)	-7.8 (5.3)	-8.9 (6.9)	0.745	0.200	0.806
Internal rotation	3.8 (6.7)	3.2 (5.6)	2.8 (5.0)	1.1 (6.4)	0.305	0.190	0.528
External moments (Nm/kg*m) (n, ACLR=25, Control=24)							
Flexion peak	1.93 (0.49) #*****	2.35 (0.39) #	2.31 (0.41) *****	2.23 (0.47)	0.227	**0.024#**	**<0.001***
Extension peak	0.23 (0.25) #	0.08 (0.36) #	0.14 (0.31)	0.08 (0.32)	0.534	**0.027#**	0.350
Adduction peak 1	0.53 (0.29)	0.58 (0.23)	0.50 (0.33)	0.51 (0.35)	0.502	0.575	0.695
Adduction peak 2	0.35 (0.24)	0.46 (0.19)	0.42 (0.30)	0.43 (0.30)	0.645	0.305	0.348
External rotation peak 1	-0.43 (0.14)	-0.56 (0.17)	-0.56 (0.18)	-0.56 (0.20)	0.111	0.070	0.072
Internal rotation peak 2	0.10 (0.06)	0.09 (0.07)	0.10 (0.06)	0.10 (0.07)	0.910	0.379	0.446

ACLR: ACL reconstruction; * Significant difference between group sides; # significant difference present between both sides; ∞ significant difference between groups; Group × side interaction indicates that there is a statistically significant difference between the sides and the group, that is, the difference between the two sides differs between groups. Group: there is a statistically significant difference between the values for groups. Sides: there is a statistically significant difference between the two sides. * Significant differences for sides between groups (between groups); # significant difference between sides (within groups); ∞ significant difference between groups;

Table 6.5. Results for post-hoc tests between-group and side-to-side comparisons during stair ascent

		Control Side 1 versus Side 2		**ACLR injured versus uninjured sides**		**ACLR injured versus Controls side 1**		**ACLR uninjured versus Controls side 2**	
		Mean difference (95%CI) and effect size	**p-value***	**Mean difference (95%CI) and effect size**	**p-value***	**Mean difference (95%CI) and effect size**	**p-value***	**Mean difference (95%CI) and effect size**	**p-value***
Angles	Flexion	0.8 (0.6-2.4) ES: 0.09	0.255	2.3 (0.8-3.8) ES: 0.23	0.003	4.5 (1.8-7.1) ES: 0.48	0.001	1.3 (1.4-4.0) ES: 0.36	0.337
	Flexion-extension excursion	1.2 (0.4-2.9) ES: 0.11	0.126	2.1 (0.6-3.7) ES: 0.20	0.009	4.0 (1.1-6.7) ES: 0.40	0.007	0.5 (2.8-3.8) ES:0.04	0.755
Moments	Flexion	0.08 (0.11-0.29) ES: 0.09	0.380	0.41 (0.21-0.61) ES: 0.48	<0.001	0.38 (0.12-0.64) ES: 0.42	0.005	0.12 (0.13-0.37) ES: 0.14	0.331
	Extension	0.06 (0.07-0.19) ES: 0.10	0.354	0.15 (0.01-0.28) ES: 0.25	0.026	-	-	_	_

ACLR: Anterior cruciate ligament reconstruction; ES: Effect size, Cohens d; *: p-values obtained Bonferroni's corrections

6.4.2 Stair descent

6.4.2.1 Spatiotemporal variables

No group, side and group x side interactions were found for the stride time and stance time during stair descent (Table 6.6). There was a significant side effect for the time taken to reach the peak of adduction moment 1 (p= 0.020). Post-hoc analysis indicated a significant difference when comparing the injured to uninjured sides of the ACLR group: the injured sides took longer than the contralateral sides to reach peak adduction moment 1 (mean difference 0.01seconds, 95%CI 0.0-0.04, p=0.006, Table 6.7). No significant difference was found when comparing the time to peak adduction of Side 1 to Side 2 for the controls (p=0.592).

6.4.2.2 Joint angles

Figure 6.9 demonstrates the linear envelopes (Mean and SD clouds) for the injured and uninjured sides of the ACLR group and the side 1 of the Control group. In the sagittal plane, the knee moved from a position of approximately 4° flexion at the time of initial foot contact to approximately 70° flexion during the propulsion phase (Figure 6.9). No difference was evident for the course of the flexion angles within and between groups. In the frontal plane, abduction/adduction angles appear to remain less than 5° for both sides of the ACLR group, however, for the control, greater abduction is evident during the propulsion phase. In the transverse plane, the knee appears to be moving from a relative position of external rotation at initial foot contact towards internal rotation during the weight acceptance and propulsion phases for both groups of participants.

No significant side effects, group effects and group x interaction effects were found for the discrete variables of the knee kinematics during the stance phase during stair descent (Table 6.6).

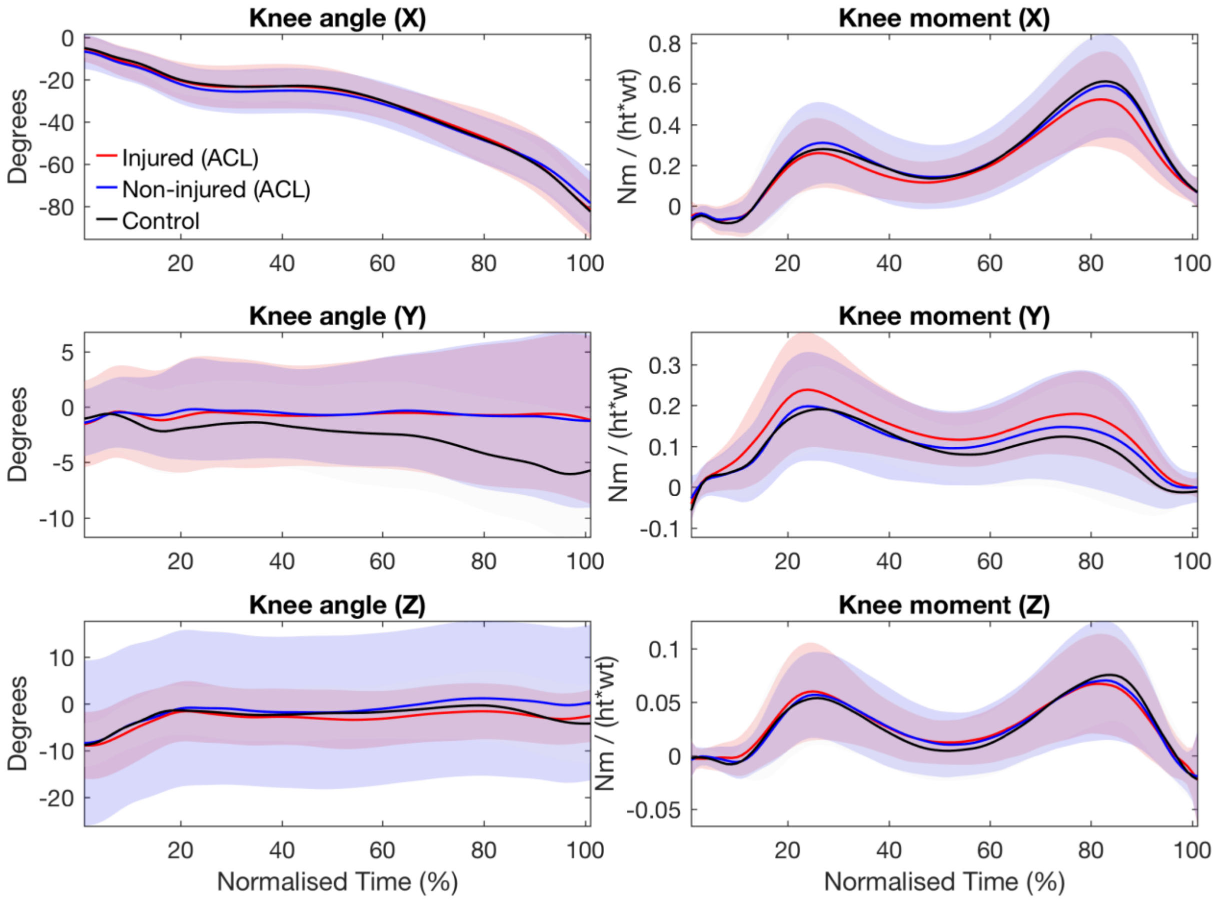


Figure 6.9 Linear envelopes (means and SDs) for angles and moments during the stance phase of stair descent in participants with ACLR.

SD clouds are provided for the injured side (red) and contralateral sides (blue) of the ACLR group. Positive values indicate knee extension angle, knee adduction angle and internal rotation angle. Positive moments include knee flexion moment, adduction moment and internal rotation moments. Black line for controls indicate movement pattern of Side 1 of Control group. 100% for the normalised time refers to the stance phase during stair ascent. X-axis defines angles and moments in sagittal plane, Y- axis defines angles and moments in frontal plane, and Z- axis defines angles and moments in transverse plane.

6.4.2.3 Moments

The knee undergoes external knee flexion, adduction and internal rotation moments during the weight acceptance and propulsion phases of stair descent. The linear envelope (Figure 6.9) indicates possible lower knee flexion moment during the propulsion phase (peak 2) for the injured sides compared to contralateral sides and the controls. In the frontal plane, both peak 1 and peak 2 adduction moments appear to be slightly higher for the injured sides compared to the contralateral sides and the controls, while there are no evident differences in the transverse plane. However, the analysis of discrete variables indicated no significant side or group effects or group x side interactions.

No group, side and group x side interactions were found for other peak moments (Table 6.6, Figure 6.9).

Table 6.6. Mean (SD) of spatiotemporal, angles, and moments: stair descent

	ACLR group		Control group				
	Side 1 (Injured side)	Side 2 (Uninjured side)	Side 1	Side 2	Group effect	Side effect	Group x side interaction
Spatiotemporal variables (n, ACLR=25, Control=24)							
Stance time (seconds)	0.77 (0.07)	0.77 (0.07)	0.77 (0.07)	0.77 (0.09)	0.810	0.642	0.584
Stance fraction (seconds)	0.64 (0.03)	0.64 (0.03)	0.63 (0.03)	0.63 (0.03)	0.203	0.684	0.795
Stride time (seconds)	1.20 (0.12)	1.20 (0.11)	1.22 (0.11)	1.22 (0.13)	0.583	0.672	0.761
Stride speed (meters/second)	0.74 (0.07)	0.74 (0.74)	0.74 (0.11)	0.75 (0.10)	0.921	0.947	0.721
Time to peak adduction moment 1 (seconds)	0.20 (0.06) #	0.17 (0.03) #	0.18 (0.03)	0.18 (0.03)	0.498	**0.020#**	0.107
Kinematics (Degree) (n, ACLR=25, Control=24)							
Phase 1 (Weight acceptance)							
Flexion	-17.0 (7.0)	-19.8 (9.1)	-17.6 (3.2)	-18.8 (5.9)	0.880	0.082	0.491
Extension	-3.0 (2.8)	-4.2 (3.1)	-4.0 (3.4)	-4.7 (5.0)	0.394	0.107	0.622
Flexion-extension excursion	14.5 (5.4)	16.3 (5.1)	13.5 (3.3)	14.0 (4.2)	0.128	0.170	0.462
Abduction	-3.3 (3.7)	-3.0 (3.2)	-3.1 (3.7)	-3.1 (3.7)	0.991	0.820	0.788
Adduction	-0.1 (5.1)	0.5 (4.0)	-0.0 (3.2)	-0.1 (5.1)	0.791	0.693	0.703
External rotation	-8.6 (8.0)	-8.21 (9.4)	-8.7 (5.1)	-10.6 (5.9)	0.471	0.539	0.337
Internal rotation	0.1 (7.4)	1.2 (8.1)	-0.2 (4.7)	-1.9 (6.1)	0.268	0.774	0.246
Phase 2 (Propulsion)							
Flexion	-67.7 (18.9)	-74.2 (16.8)	-73.4 (9.4)	-74.3 (11.7)	0.404	0.140	0.266
Extension	-14.7 (4.9)	-17.7 (7.2)	-15.5 (3.3)	-17.7 (7.2)	0.703	0.093	0.220
Flexion-extension excursion	54.0 (12.8)	58.3 (8.4)	57.90 (7.7)	58.3 (8.4)	0.248	0.436	0.583
Abduction	-5.4 (6.9)	-5.4 (6.0)	-6.4 (5.9)	-7.5 (5.0)	0.213	0.608	0.620
Adduction	1.4 (6.7)	1.7 (5.4)	-0.1 (4.8)	0.6 (4.2)	0.319	0.510	0.811
External rotation	-7.3 (5.3)	-4.8 (8.4)	-7.4 (5.9)	-7.9 (5.4)	0.279	0.392	0.184
Internal rotation	2.6 (6.2)	5.4 (7.3)	3.1 (5.9)	1.4 (6.6)	0.237	0.640	0.070

		ACLR group		Control group				
		Side 1 (Injured side)	**Side 2 (Uninjured side)**	**Side 1**	**Side 2**	**Group effect**	**Side effect**	**Group x side interaction**
External moments (Nm/kg.m) (ACLR=25, Control=24)								
Flexion	Peak 1	0.87 (0.39)	1.00 (0.50)	0.86 (0.50)	0.86 (0.30)	0.497	0.377	0.411
	Peak 2	1.65 (0.68)	1.78 (0.54)	1.73 (0.61)	1.67 (0.59)	0.929	0.664	0.173
Adduction	Peak 1	0.69 (0.32)	0.61 (0.36)	0.60 (0.26)	0.63 (0.34)	0.614	0.723	0.389
	Peak 2	0.53 (0.31)	0.48 (0.35)	0.41 (0.37)	0.39 (0.39)	0.170	0.554	0.861
Internal rotation	Peak 1	0.19 (0.12)	0.18 (0.10)	0.16 (0.12)	0.18 (0.10)	0.632	0.918	0.482
	Peak 2	0.23 (0.12)	0.23 (0.14)	0.23 (0.11)	0.23 (0.13)	0.928	0.942	0.888

* Significant difference between group sides; # significant difference present between both sides; ∞ significant difference between groups; Group × side interaction indicates that there is a statistically significant difference between the sides and the group, that is, the difference between the two sides differs between groups. Group: there is a statistically significant difference between the values for groups. Sides: there is a statistically significant difference between the two sides. ACLR: ACL reconstruction, IFC: Initial foot contact;

Table 6.7. Results for post-hoc tests between-group and side-to-side comparisons during stair descent.

		Control Side 1 versus Side 2		**ACLR injured versus uninjured sides**		**ACLR injured versus Control side 1**		**ACLR uninjured versus Control side 2**	
		Mean difference (95%CI) and effect size	**p-value***	**Mean difference (95%CI) and effect size**	**p-value***	**Mean difference (95%CI) and effect size**	**p-value***	**Mean difference (95%CI) and effect size**	**p-value***
Spatiotemporal	Time to peak adduction moment 1	0.0 (0.01-0.02) ES: 0.33	0.592	0.0 (0.00-0.04) ES: 0.33	0.006	_	_	_	_

Table 6.8. Repeatability of knee joint moments using the adopted biomechanical model.

		Flexion moment (Nm/kg*m)			Adduction moment (Nm/kg*m)		
		Mean (SD)	**ICC (95%CI)**	**SEM**	**Mean (SD)**	**ICC (95%CI)**	**SEM**
Stair ascent							
ACLR	Injured	2.01 (0.34)	0.42 (0.17-0.72)	0.20	0.52 (0.16)	0.30 (0.08-0.63)	0.10
	Uninjured	2.47 (0.27)	0.48 (0.22-0.76)	0.14	0.50 (0.06)	0.30 (0.08-0.63)	0.04
Control	Side 1	2.30 (0.03)	0.39 (0.14-0.70)	0.22	0.44 (0.08)	0.97 (0.93-0.99)	0.01
	Side 2	2.20 (0.24)	0.91 (0.82-0.97)	0.02	0.52 (0.09)	0.96 (0.92-0.99)	0.01
Stair descent							
ACLR	Injured	0.75 (0.20)	0.62 (0.24-0.89)	0.14	0.58 (0.10)	0.57 (0.32-0.81)	0.04
	Uninjured	0.83 (0.48)	0.28 (0.06-0.61)	0.17	0.55 (0.16)	0.86 (0.72-0.95)	0.02
Control	Side 1	0.72 (0.19)	0.41 (0.16-0.72)	0.11	0.56 (0.08)	0.74 (0.53-0.90)	0.02
	Side 2	0.73 (0.14)	0.54 (0.28-0.80)	0.07	0.70 (0.09)	0.92 (0.84-0.97)	<0.01

ACLR: Anterior cruciate ligament reconstruction; SEM: Standard error of the measurement; ICC: Intraclass correlation coefficient

6.4.3 Repeatability of knee joint moments using the adopted biomechanical model

For stair ascent, high to low consistency was shown for flexion moments with the ICC ranging from 0.39 to 0.91 and SEM 0.02 to 0.22 Nm/kg.m. During descent, flexion moments had a moderate to low consistency with ICC ranging from 0.28 to 0.62 and SEM from 0.07 to 0.14 Nm/kg.m, were found (Table 6.8).

For the adduction moment, during stair ascent high to low consistency between trials was shown in all groups with ICC ranging from 0.30 to 0.97 and SEM 0.01 to 0.10 Nm/kg.m. For stair descent, the adduction moment ranged from high to moderate consistency for both groups with ICC ranging from 0.57 to 0.92 and SEM from <0.01 to 0.04 Nm/kg.m. Therefore, low to high consistency was found for peak external flexion and adduction moments of the knee using 3D motion analysis in ACLR and control participants (Table 6.8).

6.5 Discussion

The primary aim of this study was to compare knee kinematics and kinetics of the ACLR knee to the contralateral limb and with the age-matched uninjured controls during stair ascent and descent. It was hypothesized that the ACLR group would have a lower knee flexion moment, and higher adduction and internal rotation moments during stair ascent and descent compared to the Control group. The first hypothesis was partially accepted as the injured limbs of the ACLR group presented with lower knee flexion moments compared to the contralateral uninjured limbs during stair ascent. The second hypothesis was partially accepted as group differences were found for the peak flexion angles in the ACLR group compared to the Control group. Interestingly, the peak knee extension moment during the second half of the ascent stance phase was higher in the ACLR injured side than the contralateral uninjured limbs. The differences in knee moments indicate altered joint loading and possible loss of control of movement, both of which can contribute to the development of early onset of knee osteoarthritis following ACL injury (Andriacchi et al., 2004).

6.5.1 Demographics

Twenty-five participants with ACLR, and 24 control age- and gender-matched participants, took part in the study. Participants with ACLR were from 2 to 10 (mean 4.7) years following surgery and had higher body mass index ($p<0.001$) compared to the Control group (Table 6.3). Higher BMI in participants with ACLR may be associated with decreased levels of physical activity. The Tegner Score found no significant difference in the sports participation for pre-injury compared to post-injury levels (pre-injury Tegner sore: 7.0/10; post-injury score: 5.0/10, $p=0.09$, Chapter 4, Table 4.2). The current amount of weekly sports participation or physical activity was not assessed in this study. Previous studies have indicated different reasons for the gradual decrease in the level of physical activities following ACLR which could be related to the presence of knee pain or strength deficits (Gobbi & Francisco, 2006) and other life events such as marriage, childbirth, change in life style, and increased job demands (Flanigan et al., 2013). Results of the KOOS indicated that the ACLR group rated the Sports/Recreation function lower than the Control group (ACLR= 75.8; controls= 98.0, $p <0.001$). Therefore, it is possible that decreased level of their physical activity in the ACLR group could have led to the higher body mass index in these participants compared with the controls.

From the KOOS scores, the participants indicated having problems with stair ascending and descending for the question about stairs in knee function and daily living (Chapter 4). More participants from the ACLR group appeared to experience symptoms during stair ascent than descent. The mean score for the KOOS question relating to stair ascent was 93/100 for stair ascent and 90/100 for stair descent. Differences were also found during stair navigation compared to Control group (Stair ascent=99/100, stair descent=98/100). There was minimal difference in the symptom rating when considering the scores for ascent and descent. Thus, symptoms alone during those activities are unlikely to explain the asymmetries during ascent compared to descent.

6.5.2 Spatiotemporal variables for stair ascent and descent

No differences were found between the ACLR and Control group for any of the variables during stair ascent and descent except for the time to the first peak adduction moment during stair descent. It was longer for the injured compared to the contralateral uninjured side during stair descent (Table 6.6). It may be a compensatory strategy used by the participants with ACLR by taking longer time to reach the peak adduction moment during the stance phase. This strategy could have helped the participants to distribute the moments in the frontal plane. Results of the current study did not find differences in other spatiotemporal variables such as stance time or stride time, which is similar to another study (Hall et al., 2012), which also indicated no differences in the stance time in participants from 2 to 18 years following surgery in young participants (mean age of 26 years) during stair ascent and descent.

A previous study from our unit and collaborators at the University of Umeå, Sweden, exploring kinematics during stair descent following ACLR (>20 years post-injury) showed the differences in speed among participants with ACLR compared with the age matched the Control group during stair descent (Sole et al., 2016). Participants of that study had higher age (45.6 years on average) and lower knee-function in activities of daily living (KOOS ADL= 84) and sports and recreation (KOOS Sports/recreation=50) on KOOS subscale compared to the current study (KOOS ADL= 95, KOOS Sports/recreation=75), indicating reduced knee function. Younger participants, better knee function, and less time since surgery in the current study compared to that study (Sole et al., 2016) could be the reason for the presence of fewer discrepancies in spatiotemporal variables.

6.5.3 Joint angles

6.5.3.1 Ascent

Participants in ACLR group exhibited significantly lower peak knee flexion angles compared to the controls during stair ascent (Table 6.4). Similar findings have been reported in previous study (Lewek et al., 2002) indicating lower knee flexion angle in ACLR group compared to the uninjured Control group. That study divided the ACLR group based on the muscle strength, and the cohort with poor muscle strength had reduced knee flexion moment during walking. In the current study, flexion-extension excursion angles were lower on the injured side compared to side 1 of Control group during stair ascent. Maximum flexion during stair ascent occurs at initial contact and it appears that this occurred with more knee flexion in the ACLR injured side, while extension did not differ between groups and sides. These small alterations in the joint angles are believed to cause a spatial shift in the location of load contact which could lead to degeneration of the articular cartilage (Andriacchi et al., 2004). Further, peak knee flexion angles during stance phase of gait were found to be progressing in participants with severe osteoarthritis (Astephen, Deluzio, Caldwell, Dunbar, & Hubley-Kozey, 2008). As the stair navigation involves greater degrees of sagittal plane range of motion, such activities could be challenging for the participants.

6.5.3.2 Descent

No significant differences in knee angles were found in all three planes during weight acceptance and propulsion phases of stair descent. Another study, Sole et al., 2016, also reported differences in temporal variables than for kinematic variables during stair descent at more than 20 years following ACL injury. In that study the participants of ACLR group walked more slowly compared to the Control group. The current study did not find differences in speed during stair descent; however, differences were present in the time to reach the first peak knee adduction moment compared to the Control group. Again it indicates a compensation strategy or persistent caution during weight bearing on the injured side during stair descent. Moreover, lack of differences in peak knee flexion angles may be due to the fact that stair descent involves less knee joint loading, as evident with peak flexion moments when compared to stair ascent. Alternatively, it may be possible that compensatory strategies are more evident in other body segments (for instance the trunk or hip) while descending stairs. This needs further investigation.

6.5.4 Moments

6.5.4.1 Ascent

Lower knee flexion moments were present on the injured side compared to the contralateral limb in ACLR group and the side 1 of the Control group during stair ascent. The mean difference between the injured and uninjured side was greater than the SEM (SEM= 0.14 to 0.20 Nm/kg.m) for both sides, therefore the differences in moments among both sides in ACLR group are not incidental. Lower flexion moments on the injured side indicate between-sides moments asymmetry and also the compensatory role played by the contralateral side by generating higher flexion moments during ambulation.

Side-to-side differences in moments are considered as a risk factor for re-injury during sports (Schmitt et al., 2012).

Higher extension moments on the injured side indicate compensatory behaviour on the injured side during ambulation. This is similar to the 'quadriceps avoidance' reported in participants with ACL deficiency where they ascended the stairs with lower external flexion moments and higher knee extension moments at 60° of knee flexion, which was interpreted as the patients' effort to avoid the quadriceps contraction (Berchuck, Andriacchi, Bach, & Reider, 1990). Participants of the current study had similar findings where they ascended the stairs with lower knee flexion moment and higher knee extension moments at 57° of knee flexion. As these participants had higher knee laxity compared to the contralateral limb (Chapter 4, Table 4.3), it may be due to participants' efforts to stabilise the knee. Other plausible reasons could be related to the lack of neuromuscular control of movement, or change in the co-contraction between hamstring and quadriceps, or it may be related to the changes in control of the hip muscles. Quadriceps phenomenon was reported to decrease following surgery in a group of participants who were tested during treadmill walking at 8 months following surgery (Knoll et al., 2004). Surprisingly, it seems to persist for long-term.

Our results are similar to other studies (Hall et al., 2012; Zabala et al., 2013) analysing the moments during stair ascent and descent. These studies also reported lower flexion and adduction moments on the injured sides in participants with ACLR in short-term (from 22 months to 34 months) (Zabala et al., 2013) and long-term (2-18 years) (Hall et al., 2012). Lower flexion moments on the injured side compared to the uninjured side are likely to indicate reduced loading at the knee joint and perhaps due to decreased neuromuscular control, and a hesitation before weight-bearing on the injured side (Andriacchi, 1990). Lower joint loading is also confirmed by the lower ground reaction force on the injured side during eccentric deceleration phase of vertical jump in another study (Baumgart, Hoppe, & Freiwald, 2017).

Lower joint loading may be associated with the progression of osteoarthritis. Altered joint mechanics including joint moments and angles can lead to onset and progression of the symptoms related to osteoarthritis by initiating cartilage degradation (Andriacchi, Koo, & Scanlan, 2009). Recent research has indicated that joint unloading, not overloading, may be associated with the process of early degeneration at the knee after ACL injury (Hall et al., 2012; Zabala et al., 2013). The lower joint moments and joint contact forces were found 6 months after injury and reconstruction in participants who developed osteoarthritis (Wellsandt et al., 2016). Participants with radiographic knee osteoarthritis walked with lower knee adduction moments and medial compartment joint contact forces compared to those without osteoarthritis early 5 years following ACLR (Wellsandt et al., 2016). Similarly, another study indicated lower knee flexion moment and lower tibiofemoral contact forces in participants with ACLR from 2-3 years following surgery compared to the Control group during walking, running and side stepping (Saxby et al., 2016). Participants who had decreased knee joint loading at 2 years following ACLR had increased risk of developing symptoms of early knee osteoarthritis 5 years following surgery (Khandha et al., 2016). That study found lower peak knee flexion angle and external flexion moments in the group of ACLR participants who developed osteoarthritis. Results of the current study in terms of decreased flexion angles and flexion moments are similar to the above-mentioned studies, though the evidence for the presence or absence of osteoarthritis was not explored in this study.

In contrast to the lower joint loading following reconstruction surgery, it is important to acknowledge that there is data to support that there is increased progression of osteoarthritis with higher joint loading in the frontal plane 5 years following ACLR

(Butler et al., 2009). That study indicated higher peak knee-abduction moment by 21% in the ACL compared with the Control group (Butler et al., 2009) and speculated that over-loading on the damaged cartilage can have deleterious effects over the joint health. It seems that the future research direction should be to perform a subgroup analysis on the participants' biomechanical characteristics in order to develop strategies to achieve 'optimal joint loading'.

Muscles responsible for controlling joint loading and flexion moments have also been shown to be influenced by the quadriceps muscles activation and force development. In an animal model, lower activation of quadriceps muscle was associated with the lower ground reaction forces in the cat knee (Herzog, Longino, & Clark, 2003), indicating the role of muscles in the joint loading. Isokinetic thigh muscle strength of the participants of the ACLR and the Control groups was presented in Chapter 4 (Table 4.3). The participants of the ACLR group had lower concentric quadriceps strength compared to the controls, and lower eccentric quadriceps strength compared to the contralateral sides. Lower joint loading, as evident with decreased external knee flexion moments, along with reduced muscle strength, may lead to the onset and progression of joint degeneration.

Gait mechanics, particularly, side to side differences in the knee flexion and adduction moments at 2 years post-surgery during walking were associated with worse patient-reported outcomes, such as KOOS pain and KOOS QOL, on average, 8 years following surgery (Erhart-Hledik, Chu, Asay, & Andriacchi, 2016). Side-to-side differences have also been found in the current study in the peak knee flexion moments in the ACLR group. KOOS results from Chapter 4 (Table 4.2) indicate higher pain (KOOS pain= 85.3) and lower quality of life (KOOS QOL= 47.0) in participants with ACLR compared to Control group, which may also be related to the differences in the movement patterns between these groups.

6.5.4.2 Descent

The adduction moments peak 1 and peak 2 were higher, based on figure 6.9 and Table 6.6, although the differences were not statistically significant. The differences did not reach significant levels, which may be due to the greater time taken by the participants with ACLR to reach the adduction moment peak 1, or it may be due to the large individual variability, as shown by the SD in the knee abduction angles. Contrasting findings have been found from the previous studies indicating the higher adduction moment (Butler et al., 2009) to lower (Zabala et al., 2013) or no differences (Hart, Culvenor, et al., 2015) in the adduction moment compared to the uninjured control group or the contralateral limb. These studies included participants from early to late duration following surgery; therefore, it is difficult to speculate on the reasons behind the variability in study findings. Studies measuring the joint contact forces are required to provide a clear picture of joint loading and contact forces in this cohort.

6.5.5 Methodological considerations

There is debate in the literature regarding the use of anatomical or functional joint estimation for the biomechanical model. Both methods have been shown to be equally reliable, with the only statistically significant difference being in kinematics during the transverse plane, of a magnitude of less than 0.78° for knee internal rotation/external rotation (Pohl, Lloyd, & Ferber, 2010). However, functional joint estimations have been reported to give more repeatable gait curves for the hip joint moments and angles during walking (Besier, Sturnieks, Alderson, & Lloyd, 2003). For the purposes of this study, for the biomechanical model, the hip joint centre was functionally estimated (Cappozzo, 1984; Leardini et al., 1999) while for the knee and ankle anatomical joint centres were used (Wu et al., 2002). The dynamic trials, as mentioned in section 6.3.3.3, were used to estimate the hip joint centre. Knee and ankle joints were calculated through the anatomical method and the static trials were used as a reference to create the knee and ankle joint centre. The joint centres were determined with respect to the shank local coordinate systems.

A further consideration was the placement of the step on top of the force plates. While embedded force plates within the stair set-up have been described (Strutzenberger, Richter, Schneider, Mündermann, & Schwameder, 2011), these were not available for this study. Movement artefacts between the step and the force plate were minimised by placing a 10 kg weight on the frame of the step, and force plate data were normalised to zero during data collection. Previous studies in the field of ACL injury and reconstruction have also used similar set-up for stair ascent and descent (Gao et al., 2012; Hall et al., 2012).

6.5.5.1 Limitations

Participants wore their own shoes during the stair ascent and descent. Shoes can influence the joint loads (Simic et al., 2011) and lower limb biomechanics (Paterson et al., 2017; Radzimski, Mündermann, & Sole, 2012). It was indicated in another study (Paterson et al., 2017) involving patients with medial knee osteoarthritis that wearing flat flexible shoes can lower knee adduction moments compared to stable supportive shoes during walking. Therefore, in the current study participants wearing standardised shoes rather than their own shoes would have resulted in different mechanics than the usual during stair navigation. The aim of the study was to measure and analyse the moments as closely as possible to their day-to-day life, where individuals prefer wearing different shoes. A decision had thus been made to test the participants in their own shoes. Trunk flexion angles were not measured during stair ascent and descent, therefore alterations in the trunk angles could have influenced the moments (Mundermann, Asay, Mundermann, & Andriacchi, 2008).

Another limitation was the use of a two-step staircase instead of a full flight of stairs. It could have influenced the speed of the participants, as it may alter their speed by knowing the point of stoppage. However, as the same set of steps was used for both groups, and no difference in the stride speed was found, the set-up of the stairs and subsequent data processing would have had similar influence for all of the participants.

Participants were not grouped according to the type of graft, as this was not the focus of the study. However, a study has indicated no differences in the moments between graft types in men (Webster & Feller, 2012a). Numerous factors could be responsible for altered moments such as quadriceps strength (Lewek et al., 2002), graft orientation (Scanlan, Blazek, Chaudhari, Safran, & Andriacchi, 2009), and type of rehabilitation (Grindem, Risberg, & Eitzen, 2015). As the participants of this study were recruited from the community, it was not possible to control for all factors. Despite the differences from other studies, the results of our study are also consistent with other studies (Hall et al., 2012; Zabala et al., 2013), indicating lower moments on the injured side and higher on the contralateral limb compared to the Control group. These are important findings irrespective of the causes for differences in the moments.

Only knee related moments and angles were explored in this study. Hip moments are likely to compensate for the lower knee moments on the injured sides (Webster, Gonzalez-Adrio, & Feller, 2004). Ankle and hip moments were not examined in this study, and should be considered in future studies. Similarly, knee moments can be influenced by the position of the trunk (Simic et al., 2011; Simic, Hunt, Bennell, Hinman, & Wrigley, 2012), and trunk angles during stair ascent and descent were not recorded, therefore, we acknowledge this limitation. Further studies are required to explore the causes of altered moments. Also, no EMG of the thigh muscles was recorded which could have provided a meaningful information about the internal loading of the knee such as the co-contraction or the contraction of the thigh muscles. Also, it may be possible that some of the participants already had development of osteoarthritis; therefore, there is similarity among the movement patterns in participants with ACLR to what is reported in patients with knee osteoarthritis in the literature. However, without the imaging data it is not possible to rule out how many participants in our cohort had presence of knee osteoarthritis.

6.6 Conclusion

Differences in kinematics and moments in participants with ACLR compared to controls suggest incomplete recovery of the knee moments, or changes in neuromuscular control and joint function following surgery. Asymmetric loading during ascent between uninjured and injured sides following ACLR and compensatory mechanisms potentially indicate risk for the development of osteoarthritis.

6.7 Summary

Based on the findings of previous chapters of this thesis, deficits in the quadriceps muscle strength (Chapter 4), along with the hesitancy in weight bearing on the injured side (Chapter 5) with potential changes in neuromuscular control of the knee appear to affect the knee joint loading, and the differences in knee flexion and extension moment were shown to persist up to 10 years following the surgery. The next chapter (Chapter 7) will explore the association of knee flexion and adduction moments with the participant-related factors.

7 Association of knee moments with the participant-related factors.

7.1 Prelude to Chapter 7

We intended to compare the knee flexion and adduction moments in participants with ACLR from 2-10 years to the 10-20 years following ACLR. This was a further exploration of the finding from the forest plots from Chapter 3 indicating that knee flexion and adduction moments may increase within increasing time following surgery. To allow a regression analysis, the time since surgery was extended up to 20 years.

The findings of Chapter 4 indicated lower quadriceps concentric and eccentric peak torque on the injured side compared to the Control group and the contralateral limb. Findings from Chapter 3 and 6 indicated lower knee flexion moments in participants with ACLR, compared to contralateral limb and controls while ascending stairs. These moments may be associated with the participant-related factors such as muscle strength, time since reconstruction, and sex of the participants. This chapter describes a cross-sectional study assessing whether the peak knee flexion and adduction moments were associated with quadriceps muscle strength, time since surgery, and the sex of the participants. Additional participants with ACLR were recruited to expand the study to include participants who had reconstruction surgery 20 years ago.

.

Chapter 7

7.2 Background

The potential relationship between muscle strength and knee flexion moments following ACLR was discussed in Chapter 3 and Chapter 6. However, literature regarding the association of moments with the participant-related factors such as muscle strength, time since surgery, sex of the participants has not yet been reviewed. The following section provides the literature exploring current understanding of a potential association of the participant-related factors with the knee moments.

7.2.1 Muscle strength and the knee flexion moment

Previous studies suggest that lower knee flexion moments during walking, jogging and drop vertical jump are associated with reduced quadriceps muscle strength in participants with ACLR (Lewek et al., 2002; Patel, Hurwitz, Bush-Joseph, Bach, & Andriacchi, 2003; Schmitt et al., 2015). Patel et al., 2003 explored a relationship between external knee flexion moments during jogging and stair climbing and isokinetic concentric quadriceps strength (at 60°/s) in 44 individuals with unilateral ACL deficiency. The muscle strength was normalised to body weight and height, and was assessed for the injured sides only. They found a significant linear association such that reduced knee flexion moments were correlated with reduced quadriceps strength (Patel et al., 2003). However, as they included participants that had not undergone reconstructive surgery, their results may not be applicable following surgery.

Association among the knee moments and muscle strength has been explored in previous studies. Lewek et al., 2002 and Schmitt et al., 2015, both explored relationships between movement patterns and muscle strength in participants with ACLR. Lewek et al., 2002 included a group of participants with ACL deficiencies and a group who had undergone

ACLR (up to 43 weeks post-surgery), and explored the potential relationship between quadriceps strength and gait patterns, specifically knee angles and moments during the early stance phase of walking and running. Muscle strength was assessed with an isometric quadriceps contraction with the knee in 90° flexion and lateral asymmetry indices were calculated (Lewek et al., 2002). Regression analysis showed a direct relationship between quadriceps muscle force and the flexion moments (Lewek et al., 2002). In a later study, participants with ACLR (averaging around 8 months post-surgery) with weaker quadriceps (LSI < 85%) demonstrated lower external knee flexion moments during jump landing compared to those with stronger quadriceps strength (LSI≥90%) (Schmitt et al., 2015). Conversely, those with nearly symmetrical quadriceps strength had landing patterns similar to uninjured participants (Schmitt et al., 2015). Collectively, results of the three studies (Lewek et al., 2002; Patel et al., 2003; Schmitt et al., 2015), suggest a positive correlation between quadriceps strength and knee flexion moments during various activities. However, an association between the knee flexion moment and quadriceps muscle strength has, to our knowledge, not yet been clearly shown in participants with ACLR in the longer-term. Quadriceps muscle strength deficits have been found up to 23 years following surgery (Tengman et al., 2014), thus it is possible that a similar relationship to that found in the above studies (Lewek et al., 2002; Patel et al., 2003; Schmitt et al., 2015) may be demonstrated in the ACLR participants in the current study.

7.2.2 Muscle strength and knee adduction moment

Knee adduction moment represents the knee loading in the medical knee compartment (Miyazaki et al., 2002) and higher adduction moment is associated with progression of osteoarthritis (Hall et al., 2017). Knee adduction moment was associated with the knee adduction angle and the ground reaction force in a cohort of healthy participants during treadmill walking at their preferred speed (Schmitz & Noehren, 2014). According to that study, 58% of variance in the knee adduction moment was explained by the knee adduction angle, and 20% by the ground reaction force (Schmitz & Noehren, 2014). It is important to consider that this study included asymptomatic young (average age = 22 years) participants, and development of knee pain or potential osteoarthritis could lead to different influences on gait and the knee moments. Adduction moments are also influenced by the knee adduction moment arm such that a higher association between peak knee adduction moment and peak frontal plane lever arm was present during walking in knees with osteoarthritis than between peak knee adduction moment and peak frontal plane ground reaction force (Hunt, Birmingham, Giffin, & Jenkyn, 2006).

There is some evidence that muscle strength can counteract the knee adduction moment by generating knee abduction moments primarily generated by quadriceps and the gastrocnemius (Shelburne et al., 2006). Although quadriceps and gastrocnemius had relatively small abduction moment arms at the knee, they can exert large abduction moments during the stance phase of normal gait because they have been arranged symmetrically about the centre of the knee in the frontal plane (Shelburne et al., 2006) . This allows the muscles to provide frontal plane knee stability during walking. This association has been explored in participants with knee osteoarthritis (Lim et al., 2009). Thirteen percent of variance in adduction moment during walking can be explained by the isometric quadriceps muscle strength (Lim et al., 2009). Walking is a lower loading activity compared to other activities of day-to day life such as stair ascent navigation and running; moreover, isometric quadriceps strength might not reflect submaximal dynamic strength. It may be the reason that no association was found by Lim et al., 2009 .

The association between quadriceps muscle strength or knee adduction moment has not been explored in participants with ACLR. If there is a positive relationship between quadriceps muscle strength and the adduction moments, strengthening the quadriceps muscle to normalise the moments could be targeted in the clinical setting. Alternatively, appropriate long-term conservative strategies can be addressed by the clinicians to offload the higher moment.

7.2.3 Moments and their association with time since surgery

As discussed in Chapter 3, it is possible that the magnitude of knee flexion or adduction moments changes over the course of time following surgery. Specifically, visual inspection of the forest plot (Figure 3.6, (5.2.1) and 3.7, (6.2.1)) indicated peak adduction moments are likely to increase over time following reconstruction. Peak adduction moments were significantly lower in participants with ACLR than in controls within the first year following surgery (average 10.3 months) during walking (Webster, Feller, et al., 2012). However, in another study, adduction moments were higher than controls at mid-term (5.3 years) (Butler et al., 2009).

Time since surgery can influence the participants' subjective perception regarding their knee function (Bodkin, Goetschius, Hertel, & Hart, 2017). Functional demands related to the knee may change throughout life with the change in personal and professional roles and preferences in life. Participants with ACLR (from 2 to 5 years) demonstrated moderate relationships with unilateral normalised muscle strength and symmetry measures of hopping performance to subjective knee function; while participants greater than 5 years since surgery indicated stronger association with the hopping task symmetry (Bodkin et al., 2017). This chapter will explore whether there is a significant relationship between the time since surgery and knee flexion and adduction moments during stair ascent and descent.

7.2.4 Recovery of knee moments for men and women following ACLR

Knee adduction moments may differ between men and women. Higher knee adduction moments normalised to the height and weight of the participants were found during walking in women compared to men with ACLR, from 3 weeks to 12 months following surgery (Webster, McClelland, Palazzolo, Santamaria, & Feller, 2012). Participants of that study were matched for age, time since surgery, and walking speed. Women demonstrated 23% higher adduction moments on the operated knee compared to men with ACLR, in this study. Another study reported lower peak knee adduction moment during walking in women, on average, 3.5 years following ACLR, compared to women controls (Patterson et al., 2014).

The difference in the pattern of recovery in the sagittal plane was found in one study. This study compared knee mechanics during walking in a group of men and women 6 months following ACLR. Women demonstrated smaller internal knee extension moments in the involved limb compared to the uninvolved limb at 6 months post-surgery. Differences in internal knee extension moments were also present in men; however, the differences were more pronounced in women (Di Stasi et al., 2015). Further, a study indicated lower knee flexion moments in women with ACLR compared to uninjured women during walking and running at an average of 5.2 years following surgery, and that chronic changes in joint loading in women may persist in long-term (Noehren et al., 2013). So the question is whether there is difference in flexion and adduction moments following ACLR in men compared to women.

The aetiology of knee osteoarthritis is multi-factorial, consisting of structural, physiological and biomechanical factors (Andriacchi et al., 2015). In terms of the biomechanical factors, higher adduction moments are associated with the onset and progression of knee osteoarthritis (Sharma et al., 1998)). Women are known to be at higher risk of development of osteoarthritis following ACLR (Li et al., 2011; Lohmander et al., 2007). Moreover, the differences in the patient-reported outcomes were reported among men and women, with significantly worse outcomes in women compared to men before and at 1 and 2 years following surgery in a study that included more than 4000 participants with ACLR (Ageberg, Forssblad, Herbertsson, & Roos, 2010). This indicates that differences in the recovery may persist among men and women following surgery. In terms of joint loading, if the recovery of knee adduction and flexion moments differs for women compared to men, it could potentially explain, in part, why women have a higher risk of developing knee osteoarthritis following ACLR.

7.2.5 Aims

The aim of this study was to assess the association between knee flexion or adduction moments with quadriceps muscle strength, time since ACLR, and sex of the participants, during stair ascent and descent in participants with ACLR.

7.2.6 Hypothesis

It was hypothesised that:

1. Concentric quadriceps muscle strength would be associated with the knee flexion moment and adduction moment during stair ascent. Higher quadriceps strength would be associated with higher knee flexion and lower adduction moments. Similarly, eccentric quadriceps strength would be associated with the knee flexion

and adduction moments during stair descent. Higher eccentric peak torque would be associated with the higher flexion and lower adduction moment.

2. Time since reconstruction influences the knee flexion and adduction moment such that there would be increase in flexion and adduction moment as the time since surgery increases.
3. The participants' sex will influence the knee flexion and adduction moment such that women would be associated with higher adduction and lower flexion moment than men.

7.3 Methods

7.3.1 Ethical approval, Study design, setting and recruitment

This was a cross-sectional study of participants with ACLR from 2 to 20 years post-surgery. All participants were recruited from the community, and the recruitment strategies have been described in Chapter 4, section 4.3.1 to 4.3.4. Participants from the cross-sectional study (Chapter 4) with ACLR from 2 to 10 years post-surgery were included. In addition, participants with 10 to 20 years post-surgery, were recruited for this study.

The STROBE statement for reporting cross-sectional studies was used to report this study. As with the cross-sectional investigation described in Chapter 6, this study was completed at the Biomechanics and Mark Steptoe Laboratories located in the Centre for Health, Activity and Rehabilitation Research (CHARR), School of Physiotherapy at the University of Otago. The University of Otago Ethics Committee granted approval for the study in the same application as for the cross-sectional study (Chapter 5, reference number H15/034, Appendix B1).

7.3.2 Inclusion criteria for ACLR participants

The same inclusion and exclusion criteria as for the ACLR group in the previous study was used, extending the time since surgery to 20 years. Thus, men and women aged between 20 and 51 years, who had undergone ACLR with any type of graft, from 2 to 20 years ago were included. Participants may have had an associated ligamentous (such as of medial collateral ligament), meniscal or chondral injury.

7.3.3 Exclusion criteria for the ACLR group

Participants for the ACLR group were excluded if they had only non-surgical rehabilitation, had undergone revision surgery for the ACL injury, had had a recurrence of injury, or had a bilateral ACL injury. Participants with other lower limb, pelvic or low back musculoskeletal injuries that needed health care over the previous 6 months or were limiting in their daily function, sports or occupational performance due to such injuries, were excluded as well. Women reporting pregnancy at the time of data collection were also excluded.

7.3.4 Procedures

Patient-reported outcomes (Tegner score, KOOS, Confidence during sports scale and SF-12) were determined as reported in Chapter 4. Isokinetic thigh muscle strength was assessed, and three-dimensional movement analysis was conducted during stair ascent and descent, as explained in Chapter 4 section 4.3.7.3, and Chapter 6, section 6.3.

7.3.4.1 Predictor variables

Muscle strength, time since ACLR and the sex of the participants were considered as predictor variables. Muscle strength and time since reconstruction were considered as continuous variables, while sex (men, women) was considered as a categorical variable.

The outcome variable for muscle strength was knee extensor peak torque of the injured side in participants with ACLR. Concentric quadriceps strength was considered as the predictor variable for the stair ascent, while quadriceps eccentric muscle strength was considered as predictor variable during the stair descent. Concentric and eccentric quadriceps strengths were selected for stair ascent and descent, respectively, to reflect the functional contraction type during those two activities (Benedetti et al., 2012).

7.3.4.2 Outcome variables

Outcome variables were: (1) peak external knee flexion and (2) peak external adduction moment of the injured side in participants with ACLR during (1) stair ascent and (2) stair descent.

7.3.5 Data processing

Data processing and analysis were explained in Chapter 4, section 4.3.8 and Chapter 6, section 6.3.1. Peak knee flexion and adduction moments were the outcome variable and were normalised for mass and height (Nm/BWXHT).

7.3.6 Statistical analysis

SPSS version 23 (IBM, SPSS Statistics 23) was used for all analyses, and the alpha level was set at 0.05. Descriptive statistics were calculated for the participant characteristics and the patient-reported outcomes.

7.3.6.1 Analysis of descriptors

Descriptive statistics (means and standard deviation) were generated for the demographic data. Mean and standard deviation values were obtained for the patient-reported data (Tegner activity score, KOOS, Confidence during sports scale and SF-12), for primary outcome measures (i.e. peak flexion and adduction moments), and for continuous predictor variables (muscle strength and time since surgery). Frequencies and percentages were generated for the categorical predictor variables (i.e. men and women).

7.3.6.2 Multiple regression analyses for the predictor and outcome variables

There are eight assumptions for the regression analysis (Field, 2009). Data met all assumptions for inclusion in the multiple regression analyses (Field, 2009) (Appendix F1and F2).

- Assumption 1: dependent variable should be measured using a continuous scale. Knee flexion and adduction moments were the continuous variables.

- Assumption 2: two or more independent variables should be either continuous (an interval or ratio variable) or categorical (i.e., an ordinal or nominal variable). For the purpose of this analysis, muscle strength and time since reconstruction were continuous variables and the sex of the participants was categorical variable. Assumptions 1 and 2 were checked manually before performing the regression diagnostics.

- Assumption 3: observations should be independent. Participants for this study were recruited from the community and had undergone surgery and rehabilitation at different hospitals and were not related to each other in any sense. This supports the assumption of independence of observations. This assumption was also checked from the Durbin-Watson statistic by using SPSS Statistics.

- Assumption 4: there must be a linear relationship between (a) the dependent variable and each of the independent variables, and (b) the dependent variable and the independent variables collectively.

- Assumption 5: homoscedasticity, where the variances along the line of best fit should remain similar as you move along the line.

- Assumption 6: multi-collinearity, which occurs when there are two or more independent variables that are highly correlated with each other. This was tested by the Tolerance/VIF values.

- Assumption 7: absence of significant outliers. This was tested using the Normal P-P plots.

- Assumption 8: residuals with approximately normally distribution. This was examined from the histograms with superimposed curves.

Multiple regression analysis were performed to assess the relationship between the quadriceps muscle strength, time since surgery, and sex of the participants with the knee flexion and adduction moments during stair ascent and descent, using the ENTER method. The dependent variables were the knee flexion and adduction moment and independent variables were the muscle strength, time since surgery, and sex. An alpha was set at < 0.05 to identify the individual predictor contribution to the models for both knee flexion and adduction moment.

7.4 Results

All data presented a distribution that was considered close to normal distribution.

7.4.1 Descriptive results

Demographic data and descriptive statistics for the predictor and outcome variables are presented in Table 7.1.

Table 7.1. Descriptive statistics

Characteristics	Mean (SD)
N	33 (16W)
Age (years)	33.0 (10.0)
BMI (kg/m^2)	26.3 (3.3)
Injured side: left/right	21 left (17 right dominant)/12 right (12 right dominant)
Time since ACLR (years)	7.0 (4.1) years (range- 2-17 years)
Graft type	17 Hamstring, 14 Patellar tendon, 2 Unknown

ACLR: anterior cruciate ligament reconstruction; W: women; N: number; BMI: body mass index; SD: standard deviation.

Thirty-three participants took part in this study, including 25 (from 2 to 10 years following surgery) who were also included in the study presented earlier (in Chapter 6). Eight additional participants (10 to 20 years following ACLR) were recruited for the current study. Three participants did not take part in the muscle strength test which was conducted in a second session of data collection in the laboratory. Reminders were sent to those participants to complete that session; however, no response was obtained from them. One of the participants developed pain following their participation in the Biomechanical study on day 1 (three-dimensional movement analysis), and thus was excluded from the muscle strength test. For another participant, testing was stopped in the middle of the test when she developed pain during the eccentric test. Therefore, data from 5 participants for the muscle strength were not included in the analysis.

Table 7.2. Descriptive statistics for patient-reported outcomes of the ACLR cohort (n = 33)

Type of outcome	Mean (SD)
Tegner scores	
Before injury	7.0 (2.0)
After surgery	5.3 (2.4)
Confidence during sports	42.0 (13.0)
KOOS	
Pain	84.5 (13.0)
Symptoms	55.3 (11.3)
ADL	95.0 (8.0)
Sports recreation	77.1 (16.0)
Quality of life	47.1 (21.0)
KOOS4	66.0 (12.0)
Short form-12 Health survey	
PCS	53.7 (5.0)
MCS	53.0 (6.0)

Tegner scores (0 = worst to 10 =highly active); KOOS: Knee Osteoarthritis Outcome Scale; (KOOS, all domains: 0 = worst to 100 = best); ADL: Activities of daily living; Confidence during sports (0 = worst to 80 = best); PCS: Physical Component Scale; MCS: Mental Component Summary Scale.

Patient reported outcomes are presented in Table 7.2. Based on the Tegner Activity Scale, results indicated a reduction in the level of physical activities of participants with ACLR (Pre-injury=7, competitive sports such as tennis, athletics; recreational sports such as soccer, squash, after surgery = 5.0 work, heavy labour, competitive sports such as cycling, cross-country skiing). Results from the Confidence during Sports Scale indicated that, as a group, participants still had decreased confidence in their knee (42/80). Results of KOOS indicate that participants had good function with activities of daily living (KOOS ADL=95), yet still experienced knee-related symptoms (KOOS- Symptoms=55) and impaired knee function during sports and recreational activities (KOOS- Sports and recreational activities=77). Overall, they scored low quality of life (KOOS- Quality of life: 47.1) and health-related quality of life as defined by the SF-12 Health Survey (PCS= 53.7, and MCS=53.0).

Table 7.3. Mean of predictor and outcome variables of injured and uninjured sides

Characteristics	Mean (SD)
Muscle strength (Peak torque, Nm/Kg)	
Quadriceps concentric (Injured side)	2.12 (0.61)
Quadriceps concentric (Uninjured side)	2.40 (0.60)
Quadriceps eccentric (Injured side)	2.40 (0.70)
Quadriceps eccentric (Uninjured side)	2.80 (0.93)
*Stair ascent (Peak moments, Nm/Bw*ht)*	
Flexion moment (Injured side)	2.00 (0.48)
Flexion moment (Uninjured side)	2.41 (0.40)
Adduction moment (Injured side)	0.52 (0.29)
Adduction moment (Uninjured side)	0.59 (0.24)
*Stair descent (Peak moments, Nm/Bw*ht)*	
Flexion moment (Peak 1) (Injured side)	0.83 (0.43)
Flexion moment (Peak 1) (Uninjured side)	1.04 (0.45)
Adduction moment (Peak 1) (Injured side)	0.66 (0.38)
Adduction moment (Peak 1) (Uninjured side)	0.64 (0.40)

Peak torque normalised for weight of the participants (Nm/kg); moments normalised by the weight and height of the participants (Nm/Kg.m), variables of the injured sides were included in the regression analysis. (n=33)

7.1.1.1 Multiple regression for the knee flexion and adduction moment during stair ascent

Multiple regression analysis demonstrated that concentric quadriceps strength and sex were independent predictors for peak knee flexion moments during stair ascent such that quadriceps strength (b=0.738, p< 0.001, Figure 7.1, Table 7.4) and sex (b=0.396, p= 0.026) contributed significantly to the knee flexion moment. Regarding sex, women presented positive association with the flexion moments. Time since surgery (b=0.017, p= 0.283) did not contribute to the knee flexion moment. This model accounted for 55.7% of the total variance in peak knee flexion moment (adjusted R^2 =0.506, F=10.9, p <0.001) (Table 7.5). The major variance in the model is from the concentric muscle strength followed by the sex of the participants.

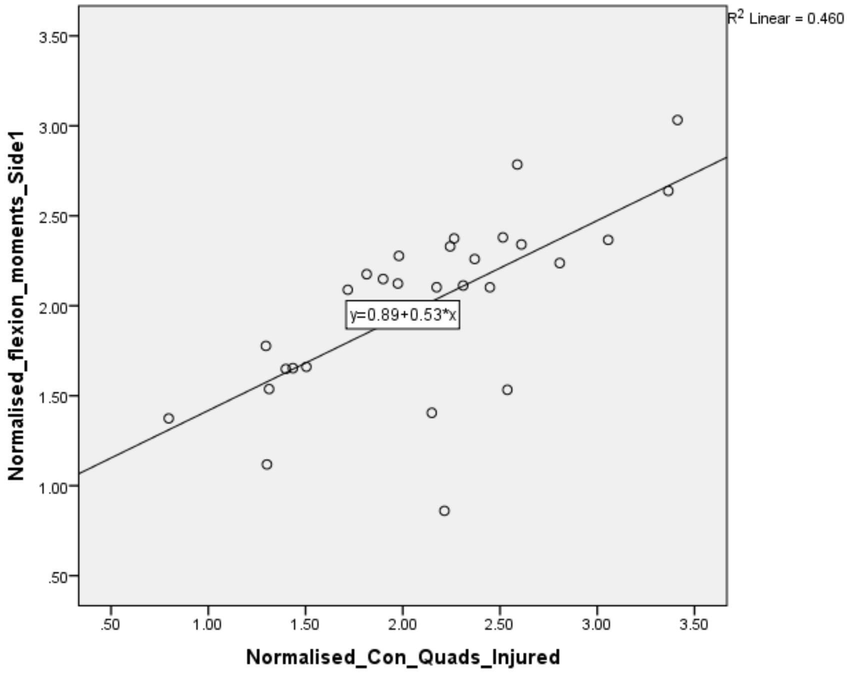


Figure 7.1. Scatter plot depicting the relationship between the peak knee flexion moment and concentric quadriceps strength during stair ascent.

For knee adduction moments, the multiple regression analysis demonstrated no significant relationship with quadriceps strength (b=-0.032, p= 0.796), or time since surgery (b=0.002, p= 0.886), sex (b=-0.149, p=0.333). This model accounted for 5% of the total variance in peak knee adduction moment (adjusted R^2 = -0.057, F=0.481, p =0.698) (Table 7.5).

7.2.1.1 Multiple regression for the knee flexion and adduction moment during stair descent

Multiple regression analysis demonstrated that none of the predictors were associated with the flexion moment such that eccentric quadriceps peak torque (b= 0.140, p= 0.321), time since surgery (b= -0.018, p= 0.353), and sex (b= 0.031, p= 0.875) showed no significant relationship. This model accounted for 7% of the total variance in peak knee flexion moment (adjusted R^2 = -0.037, F=0.664, p =0.582) (Table 7.5).

Multiple regression analysis demonstrated that none of the predictor variables were associated with the adduction moment. Neither the eccentric quadriceps peak torque (b= -0.081, p= 0.523, Table 7.4), nor the time since surgery (b= -0.025, p= 0.164) or the sex (b= -0.042, p= 0.813) contributed significantly to the adduction moment. This model accounted for 9% of the total variance in peak knee adduction moment (adjusted R^2 = -0.013, F=0.782, p =0.466) (Table 7.5).

Table7.4 Multiple regression analysis of predictors of the flexion and adduction moment of the involved limb during stair navigation.

Independent variables	Dependent variables (Moments)	Unstandardized coefficients		Standardized coefficients	
		B	**SE (B)**	**β**	**p-value**
Stair ascent (n=29)					
Concentric quadriceps peak torque	Flexion	0.738	0.135	0.948	**<0.001***
Time since surgery (years)		0.017	0.015	0.150	0.283
Sex		0.396	0.168	0.418	**0.026**
Concentric quadriceps peak torque	Adduction	-0.032	0.121	-0.066	0.796
Time since surgery (years)		0.002	0.014	0.029	0.886
Sex		-0.149	0.151	-0.256	0.333
Stair descent (n=29)					
Eccentric quadriceps peak torque	Flexion	0.140	0.139	0.229	0.321
Time since surgery (years)		-0.018	0.019	0.019	0.353
Sex		0.031	0.193	0.037	0.875
Eccentric quadriceps peak torque	Adduction	-0.081	0.126	-0.145	0.523
Time since surgery (years)		-0.025	0.017	-0.278	0.164
Sex		-0.042	0.175	-0.054	0.813

Peak torque normalised for weight of the participants (Nm/kg); moments normalised by the weight and height of the participants (Nm/Kg.m).

Table 7.5 Model summary for the regression analysis.

Variables	R	R^2	Adjusted R^2	p
Stair ascent (Moments)				
Flexion	0.746	0.557	0.506	**<0.001**
Adduction	0.229	0.053	-0.057	0.698
Stair descent (Moments)				
Flexion	0.272	0.074	-0.037	0.582
Adduction	0.309	0.095	-0.013	0.466

Moments normalised by the weight and height of the participants (Nm/Kg.m), R: multiple correlation coefficient, R^2; coefficient of determination, Adjusted R^2: coefficient of multiple determination.

7.5 Discussion

The study investigated the relationship between the quadriceps muscle strength, time since ACLR, and sex of the participants with the knee flexion and adduction moments during stair ascent and descent in participants with ACLR. It was hypothesized that quadriceps concentric muscle strength would be associated with the peak knee flexion and adduction moments during stair ascent, and eccentric quadriceps strength would be associated with the knee flexion and adduction moments during stair descent. The first hypothesis was partially supported, as a significant association was found between concentric quadriceps strength and the flexion moment during stair ascent. However, no statistically significant association was present between quadriceps peak torque and the adduction moment during stair ascent and descent.

Lower knee flexion moments during stair ascent were correlated with the quadriceps index during isometric contraction in a study at 21 weeks on an average following surgery (Lewek et al., 2002). Results of the current study were similar to that of Patel et al., 2003 who found a significant association between knee flexion moment and concentric quadriceps strength at during stair navigation in participants with ACL-deficiency. Similarly, quadriceps femoris strength deficits were associated with the sagittal plane knee mechanics during landing 8 months, on an average, following ACLR. The findings imply that strengthening the quadriceps may improve the knee flexion moment in participants with ACLR and can help to restore the sagittal plane moment asymmetry.

Although Shelburne et al., 2006 suggested that quadriceps muscle function contributes towards frontal plane knee mechanics, the relationship between the adduction moment and quadriceps muscle strength is poorly understood in the literature. No association was found between quadriceps muscle strength and the adduction moment during stair ascent or descent in the current study. These results are similar to a previous study exploring the association between isometric knee strength (normalised to participants weight) and knee adduction moment in participants with osteoarthritis during walking. That study found no association between these variables (Lim et al., 2009). The lack of a significant association between adduction moment and muscle strength could be explained by the type of contraction participants are exposed to during the testing. During walking, the quadriceps muscles are functioning concentrically, and isometric contractions do not reflect that. This may explain the reason for lack of association between quadriceps muscle strength and knee adduction moments, both during stair ascent and descent, despite muscle strength being measured isotonically. Although we assessed both concentric and eccentric muscle strength for the quadriceps, no significant relationship was found with knee adduction moments. We included the PT of the injured side in the analysis. It is possible that exploring the LSI (thus, comparing muscle strength of the injured to the uninjured side) would better explain differences in knee moments. This will be a future investigation. There are several potential explanations for the lack of association between muscle strength and the adduction moment in the current study. Firstly, knee adduction moments seem to be related to the knee extensor power (Calder et al., 2014) and the endurance of the quadriceps muscle, rather than the muscle strength (Lee, Lee, Ahn, Park, & Lee, 2015). This is supported by findings from a randomised clinical trial exploring the effects of a strengthening programme on knee adduction moments during walking in patients with knee osteoarthritis (Bennell et al., 2014). The 12-week programme entailed neuromuscular training and quadriceps strengthening for participants with knee osteoarthritis during walking. The results indicated no significant change for knee adduction moments following the programme (Bennell et al., 2014). Secondly, adduction moments are also influenced by the knee adduction moment arm

(Hunt et al., 2006). In that study, participants with clinically and radiologically diagnosed osteoarthritis were recruited, and they exhibited increased peak knee adduction moments compared to less affected knees, even though the peak frontal plane ground reaction force was less, suggesting that the larger peak adduction moments were mainly the result of the larger lever arm magnitudes exhibited in knees with osteoarthritis. Lastly, muscle strength was measured with the isokinetic dynamometer at the 60°/sec in the current study, while another study has indicated the association between the adduction moments and total work of quadriceps at 180°/sec rather than at 60°/sec and also indicated that 60°/sec may not be the most valid speed (Lee et al., 2015). Speed of 60°/sec was used in this study for muscle strength testing as it is more likely to find the deficits during maximal strength testing compared to endurance testing.

No association was found among the knee flexor moment and the eccentric quadriceps strength during the stair descent. Quadriceps work eccentrically during the stair descent; therefore, an association was expected among the variables. However, no association was found which may be due to the fact the moments may depend on various other factors such as angle of the force vector, trunk angle, or hip abduction moment during stair descent. Perhaps a further study with EMG from the muscles could help to explore this association further.

Based on findings from the systematic review involving visual inspection of the forest plot (Chapter 3, Figure 3.6 and 3.7), it was also hypothesised that time since surgery would influence the knee flexion and adduction moment. No such association was found in the data of the present study. This may be partly because knee flexion moments continue to be lower compared to the contralateral knee and the uninjured Control group (Hall et al., 2012; Wellsandt et al., 2016) and at 2 to 10 years following surgery (Chapter

6). However, regarding the adduction moment, limb symmetry scores were 88% and 103% for stair ascent and descent respectively. Moments may be influenced by many factors as described above, and the participant related-factors such as their muscle strength and trunk angles during ambulation. We were unable to consider all the factors in this study; therefore, it is difficult to enlist the reasons for no known associations among the moments and the time since reconstruction.

Normalised peak flexion moments seemed to be higher in women in the current study. Knee flexion moment is known to have greater influence on cartilage such that tibial cartilage changes at 5 years were associated with the baseline knee flexion moment in patients with knee osteoarthritis (Chehab, Favre, Erhart-Hledik, & Andriacchi, 2014). This indicates that strengthening the quadriceps to optimise the knee moments may be helpful, particularly for women. Interventions need to be carefully designed and executed in these participants by taking knee symptoms into account, as the higher loading beyond the optimal levels can be disruptive to the cartilage (Andriacchi et al., 2004). Participants should be educated regarding the role of muscle strength and maintenance of knee health in the long-term. Results regarding the association of adduction moment with the participant sex remain inconclusive, as this study did not shown any significant association. Previous studies have indicated higher moments in women compared to men from 3 weeks to 12 months post-surgery (Webster, McClelland, et al., 2012), and lower adduction moment compared to the women controls at 3.5 years following surgery (Patterson et al., 2014). Future studies should focus on exploring the differences in joint loading in men and women along with patient-reported outcomes in the long-term following surgery.

Participants had reduced levels of physical activities compared to pre-injury level (Tegner scores = 5, heavy labour, competitive sports- cycling, cross-country skiing, recreational sports- jogging on uneven ground at least twice weekly) and confidence during sports (Confidence during sports scale= 42) overall. On average, the participants scored low knee-related quality of life (KOOS-QOL=47.0) as a group, which could potentially be due to the presence of knee-related symptoms (KOOS symptoms= 55.0) and knee function during sports (KOOS sports/recreation= 77.0). However, the SD (21.0) for quality of life indicated a wide range, so while some participants considered their quality of life to be low, others rated this as being high. Participants' low average knee-related quality of life 2 to 17 years following surgery is an important finding, as the average age of these participants was 33 years (range 21 to 51) at the time of data collection. A recent study also explored quality of life in participants with ACLR, comparing those that reported poor quality of life with those reporting high quality of life, 5 to 20 years post-surgery (Filbay, Ackerman, Russell, & Crossley, 2016; Filbay et al., 2014). Poor long-term QOL outcomes were related to not returning to sport, higher body mass index, contralateral ACLR, and subsequent knee surgery in people with knee difficulties (Filbay et al., 2016). The current study excluded participants with contralateral ACLR and subsequent knee surgeries, so these were not influencing factors in this study. However, the body mass index of five participants was within in the 'overweight' category (>30 kg/m^2), which potentially could have influenced the knee mechanics (Messier, Gutekunst, Davis, & DeVita, 2005). However, as the muscle strength and moments data were normalised to the weight of the participants, there was less influence of the participants' weight on the overall study results. Higher body mass index is associated with more depressive symptoms and worse quality of life in men (Filbay et al., 2016). Fear of re-injury is known to influence the quality of life up to 20 years following ACLR (Filbay et al., 2016). Participants expressed a fear of injury up to 10 years post-surgery in the mixed-method study (Chapter 5) and also lower scores in the confidence during sports scale (Table 5.2), indicating the presence of fear of injury during sports. This may have also influenced the quality of life in this group of participants. However, no information related to the return to sports following surgery by these participants was collected in this study. Therefore, we are unable to count on this factor. Based on the Tegner scores, the present levels of sports were lower than the pre-injury levels (Table 7.2).

7.5.1 Limitations

This study included participants with different types of grafts, which may influence muscle strength recovery. Different types of grafts influence the thigh muscle strength up to 2 years following surgery (Xergia, McClelland, Kvist, Vasiliadis, & Georgoulis, 2011). However, the type of graft has not been found to influence the quadriceps and hamstring muscle strength 6 years following surgery (Keays et al., 2007). As participants of this study were more than 2 years post-surgery, grouping the participants with different grafts would not have influenced their muscle strength. Participants with or without meniscal injuries were recruited. Presence of meniscal injuries influence the knee mechanics, which could have influenced the results of this study (Lohmander et al., 2007).

The use of skin marker to monitor lower limb movement can generate artefacts during the data collection due to the movement of the markers on the skin. In addition, there is intra-assessor subject variability during placement of skin markers. However, only one researcher (MK) applied all the markers on the participants, thus reducing differences that may have been due to inter-assessor marker placement, each individual was exposed to the same amount of artefact. Movement of the skin markers can be more in individuals with high body mass index.

Other techniques which allow for the bone to be directly imaged such as fluoroscopy and stereoradiographic systems cannot be utilized during stair ascent and descent due to limitations of restricted fields of view. Therefore, motion analysis at present is the most feasible way to measure kinematics.

Dependent variables only on the injured side of the participants with the ACLR were analysed for the purpose of this study, and not on the contralateral side or in a Control group. It is possible that including limb symmetry scores for flexion and adduction moments and muscle strength, instead of the actual values for the injured sides, may have shown significant relationships between predictor and outcome variables. As the aim of current study was to explore the associations among the muscle strength and moments on the injured side in order to develop treatment protocols to optimise the moment symmetry, only the variables of injured side were considered in the analysis instead of the limb symmetry index. Future research should examine whether these correlations also occur in asymptomatic subjects and in the contralateral limb of participants with osteoarthritis.

Speed of 60°/sec was used in this study rather than 180°/sec for muscle strength testing as it was more likely to find the deficits during maximal strength testing compared to endurance testing. Another possibility was to test at both of the speeds; however, due to time constraints during data collection it was not possible to do testing at both speeds. Also, testing at both speeds would have led to fatigue, which predisposes participants to the risk of reinjury. During data collection, participants immediately followed the data collection session for single-leg hop testing, this would have put the participants at risk of reinjury.

7.6 Conclusion

Joint moments can be related to different parameters. This study indicated the association of the concentric muscle strength and sex of the participants with the knee flexion moment during stair ascent. More attention should be given to the women participants while training to restore the moments, as the study has indicated their tendency towards increase in flexion moment. This is an important finding, and future studies should explore this association further.

7.7 Summary

The biomechanical deficits on the injured side in participants with ACLR are related to the muscle strength and hesitancy on weight bearing on the injured side. Behavioural modifications due to fear of injury as discussed in Chapter 5 have huge impact on the movement pattern. These are the important findings and clinicians should focus on the psychological aspects of the injury during the rehabilitation period.

8 Chapter

Summary and recommendations

8.1 Background

The overarching research question this thesis explored was: 'Do physical, psychosocial, biomechanical and knee function-related impairments persist following ACLR in participants' up to 20 years following surgery?' This chapter discusses the overall findings of the studies conducted and their contributions to the existing literature in the fields of sports physiotherapy and clinical biomechanics. The specific aims of this chapter are to: (1) provide a concise summary of the results of the thesis; (2) discuss a conceptual model of how biomechanical, psychological and inflammatory factors can determine overall outcomes of ACLR; (3) discuss the implications for clinical practice from the findings of this thesis; (4) highlight the strengths of the thesis; (5) acknowledge the limitations of the thesis; (6) recommend future research directions; (7) draw conclusions based upon the key results.

8.2 Overall summary of results

Through the series of interconnected studies, this thesis has explored patient-reported outcomes, quadriceps muscle strength, physical performance, knee laxity and the biomechanics of the injured knee following ACLR compared to Control group data. A mixed-method approach was used, combining quantitative and qualitative study designs to ensure an in-depth study of the data obtained. Firstly, Chapter 1 explored the gap in the research field which highlighted the need to explore the long-term outcomes of ACLR. Chapter 2 explored the literature related to the muscle strength, physical performance, patient-reported outcomes, and quality of life in participants with ACLR. A systematic review and meta-analysis was conducted to explore and compare the knee moments and angles in participants with ACLR compared to controls during walking, running and stair navigation (Chapter 3). This review highlighted the dearth of studies investigating the moments and angles during high loading activities in the long-term following ACLR. Therefore, the subsequent cross-sectional study (Chapter 6) compared knee moments and angles between participants of the ACLR and Control groups (2 – 10 years post-surgery). A cross-sectional study compared the patient-reported outcomes, isokinetic muscle strength of quadriceps and hamstrings, physical performance, and anterior-posterior knee laxity between an ACLR group (2 – 10 years post-surgery) and a Control group (Chapter 4). Further mixed-method study provided deeper insight into the patients' perspectives related to the effect of the injury and surgery on their lives (Chapter 5) and that of the Control group during stair ascent and descent (Chapter 6). Lastly, the association between participant-related factors and the knee moments during stair ascent and descent were explored in a group of participants with ACLR, 2 to 20 years post-surgery (Chapter 7). Following are the research questions for each study along with key results.

1. *Do the differences persist in the knee joint angles and moments in participants with ACLR compared to the contralateral limb and with age-matched controls during walking, stair climbing, and running? What is the time course of recovery of those biomechanical variables following ACLR?*

A systematic search was performed on the electronic databases using specific keywords. Based on the inclusion and exclusion criteria, 31 studies were included in the systematic review, and a meta-analysis was performed on 27 studies (Chapter 3). A systematic review with meta-analysis found that joint kinematics were restored, on average, 6 years following reconstruction, but joint moments were still low 4-5 years following the surgery. There was strong to moderate evidence for no significant difference in peak flexion angles between ACLR and Control groups during walking and stair ascent. Although the knee adduction moment was lower at 3 years, by 4-5 years it was higher compared to uninjured individuals. Peak knee flexion moments were still lower after 5 years of surgery in participants with ACLR than in uninjured controls. Differences in the knee moments on the injured side were more apparent compared to the contralateral limb, indicating the bilateral effect of the unilateral injury. Lower moments indicate reduced loading at the knee joint. Findings indicated that knee moments were not fully restored following reconstruction, even a few years after surgery. Optimal joint loading may need to be achieved, for which long-term maintenance programmes, including self-management of the knee along with patient education, is required. Participants may need ‘booster’ sessions of exercise prescription after a few years following surgery.

2. *Do the differences persist between the patient-reported outcomes, muscle strength, physical performance, and knee laxity in participants with ACLR from 2 to 10 years following surgery compared to the Control group?*

This cross-sectional study included 25 participants with ACLR from 2 to 10 years following surgery and 24 age- and gender-matched uninjured controls. Patient-reported outcomes, muscle strength, physical performance, and knee laxity data were collected using an electronic questionnaire (comprising the Tegner activity scale, KOOS, Confidence during sports scale, and the SF-12), isokinetic muscle strength testing, single-leg hop testing, and anterior to posterior knee laxity measured with a KT-arthrometer. Data of participants with ACLR were compared to the contralateral limb and the Control group using a repeated measures ANOVA (Chapter 4). Patient-reported outcomes indicated the presence of knee-related pain and symptoms, and low knee-related quality of life in ACLR group compared to the Control group and KOOS, respectively. The injured side had statistically significant lower concentric hamstring and eccentric quadriceps strength compared to the contralateral side within the ACLR group. Significantly, lower concentric hamstring peak torque and eccentric quadriceps peak torque were found when comparing the injured to the contralateral uninjured sides. The concentric quadriceps peak torque of the injured ACLR sides were significantly lower compared to the controls side 1, similarly for hamstring peak torque of the injured sides in ACLR group were significantly lower compared to controls.

Outcomes of the single-leg hop revealed significant within-group differences with lower jump distance on injured sides compared to the contralateral sides in the ACLR group. Interestingly, a higher jump distance was evident for the contralateral sides in the ACLR group compared to the side 2 of Control group, indicating reduced physical performance only on the injured sides in ACLR group. Significant within- and between-group differences were present for knee laxity in the sagittal plane. Higher laxity on the injured side was present compared to the contralateral side in the ACLR group and side 1 of the Control group. Overall, participants with ACLR had lower muscle strength, poor physical performance as assessed by single-leg hop, and higher laxity on the injured side. A possible explanation for reduced muscle strength and knee function is likely to be due to lower activation of quadriceps muscles (Hart et al., 2010), reduced proprioception (Bonfim et al., 2003) and other factors as explained in Chapter 2 section 2.5.1 and Chapter 4 section 4.8. Further ACL injury is associated with less activation of the sensory cortex (Valeriani et al., 1996) and increased activation of the contralateral motor cortex (Grooms et al., 2017), and thus also has effects on the central nervous system

3. *What are the participants' experiences in relation to physical activity, sports, occupation and quality of life more than 2 years following ACLR?*

Ten of the participants of the above cross-sectional study (2-10 years following ACLR; 7 female; aged 20 to 52 years) also participated in individual face-to-face semi-structured interviews (Chapter 5). The patient-reported outcomes were analysed descriptively and the interview data were analysed using a general inductive approach. Participants had good knee function in activities of daily living, yet still scored low on the quality of life scale as per KOOS and SF-12. The Sports confidence scale indicated low confidence and fear of re-injury. Three overlapping themes were identified from the interviews: 'Continuum of fear of re-injury and confidence', 'live life normally' and 'need of reassurance and the maintenance of knee health'. The ACL rupture leads to long-term fear of injury and behavioural manifestations, with fluctuating levels of confidence during specific sports activities. Participants were concerned about the future risk of re-injury and osteoarthritis. The findings highlight the importance of considering individual-specific strategies as part of rehabilitation following ACLR, and should plan continued knee function maintenance exercises according to individual needs.

4. *Do the differences in the peak knee angles and moments persist in participants with ACLR compared to the Control group from 2 to 10 years following surgery?*

The biomechanical cross-sectional study (Chapter 6) included 25 participants with ACLR from 2 to 10 years following surgery and 24 age- and gender-matched uninjured controls. Three-dimensional movement analysis was performed during stair ascent and descent. Peak knee angles and moments in all three planes were calculated during stair ascent and descent. Differences in knee flexion angles were found, with lower peak knee flexion angle during stair ascent. Results also showed lower knee flexion moments on the injured side compared to the contralateral limb in participants with ACLR, indicating reduced joint loading. Higher knee extension moments were found on the injured side in the

ACLR group. Lower flexion moment and higher extension moment on the injured side indicates the presence of adaptive strategies in participants with ACLR. Lower loading on the injured side may be due to a combination of reluctance or hesitation to bear weight on the injured side, reduced muscle strength, and potential neurophysiological consequences of the injury and surgery.

5. *Are the knee flexion and adduction moment associated with the muscle strength, time since reconstruction and the participant sex on the injured side in participants with ACLR?*

This study (Chapter 7) included 29 participants with ACLR from 2 to 20 years following surgery. The kinetic data, including the peak knee flexion and adduction moments, were collected using three-dimensional motion analysis during stair ascent and descent. The isokinetic data were collected for peak torque concentric and eccentric quadriceps muscle strength. Moment data were normalised for weight and height of the participants. Muscle strength data were normalised for participants' weight. Regression analyses were performed to explore the association between the moments and the participant-related data. Results found that concentric quadriceps peak torque and the sex of the participant were 55% responsible for the variance in the first peak knee flexion moment during stair ascent. Women showed an increase in knee flexion moments compared with men. There was no significant association between the knee flexion moment and the time since surgery (Chapter 7). Knee adduction moments were not associated with the quadriceps muscle strength, sex, and the time since surgery during stair ascent and descent. The association of the knee flexion moment with concentric quadriceps strength is an important finding. This theoretically implies that quadriceps strength may be used as an indicator for knee flexion moments during stair ascent. This also implies that restoring the concentric quadriceps muscle strength may help in optimising the moment symmetry in participants following surgery. Women may need careful administration of rehabilitation support in the longer-term as indicated by the association of sex of participants with the flexion moments. Also, the increase in flexion moments indicates higher loading in women; therefore, this may mean that if loading is increased beyond the optimal levels on the cartilage which is associated with concomitant injuries in 16-46 % cases (Brophy, Zeltser, Wright, & Flanigan, 2010), it may lead to a greater predisposition of women for knee osteoarthritis following the surgery.

8.3 Factors influencing the clinical outcomes in patients with ACLR: A conceptual model.

An ACL injury is caused by a high-force event causing isolated ACL injury or also injuring multiple knee structures such as the joint cartilage, subchondral bone and menisci (Brophy et al., 2010). The injury event also initiates a series of changes in the joint which involve biomechanical and biochemical changes (e.g. inflammation and metabolic imbalances of tissue turnover) following injury (Beynnon et al., 2005; Frobell et al., 2008), known to initiate the joint degenerative changes following injury (Cattano et al., 2013). Regarding the treatment approach, surgical treatment is considered as the option, especially for those patients who aim to return to competitive sports. However, only 55% of the patients are able to return to the same level of sports within a year following the surgery (Ardern et al., 2014).

Considering the outcomes of the ACLR, participants are at high risk of post-traumatic osteoarthritis. The onset and progression of post-traumatic osteoarthritis is a complex and multifactorial process, and involves an interaction between biochemical and biomechanical factors. Higher levels of inflammatory markers are known to initiate the inflammatory process immediately following the injury (Li, Chen, & Chen, 2015), but the levels of inflammatory markers have been found to lie within the normal ranges at 8 years following surgery (Åhlén et al., 2015). Other than the altered kinetics and kinematics (Swärd et al., 2010), deficits in muscle strength (Petersen et al., 2014) are known to influence the short and long-term outcomes.

Outcomes of ACLR are dependent on numerous factors including psychosocial components: self-esteem and internal locus of control (Christino et al., 2016), fear of re-injury and lower confidence; concomitant injury to the other joint structures such as cartilage, menisci and joint capsule; surgical techniques (Scanlan et al., 2009), type of graft (Sherman & Banffy, 2004), timing of surgery (Salmon et al., 2005), and femoral canal orientation at the time of surgery can all play important roles in determining the overall outcomes. Among the modifiable factors, intense pre-operative rehabilitation (Eitzen, Moksnes, Snyder-Mackler, & Risberg, 2010) has led to clinically significant improvement in the knee function post-operatively. Similarly, post-operative rehabilitation along with the patient motivation and goal-setting during rehabilitation have been seen to deliver favourable surgical outcomes. Repeated functional testing throughout the pre-and post-operative rehabilitation to provide feedback has been related to improved outcomes after ACL rehabilitation (Grindem et al., 2015). Pre- and post-operative rehabilitation should be combined with goal-setting, and quality patient education and feedback, to improve the outcomes.

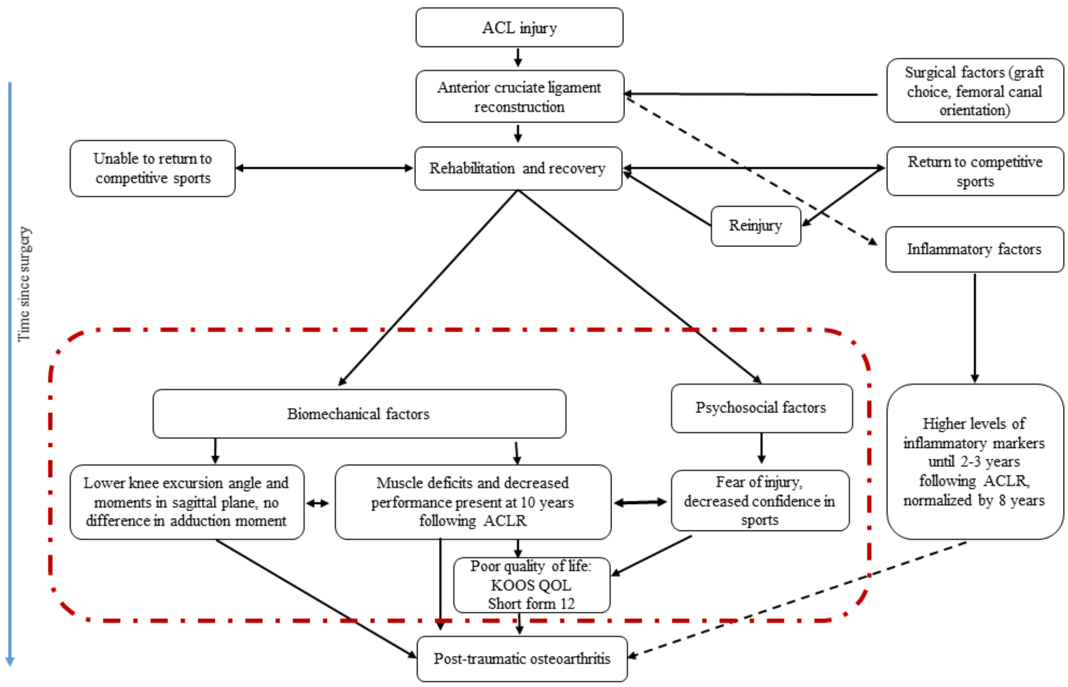


Figure 8.1. Factors influencing the clinical outcomes in patients with ACLR: A conceptual model.

The dotted red line represents the factors related to the outcomes of surgery explored in this thesis.

The results of this PhD thesis (highlighted in red-dashed outline, Figure 8.1) indicate that among the biomechanical factors, joint loading, as defined by knee flexion moments in the sagittal plane during stair navigation, were not restored compared to the contralateral limb or a Control group. Specifically, lower levels of loading were found in the sagittal plane on the injured side compared to the contralateral limb (Chapter 6). This finding is similar to the systematic review (Chapter 3), where the meta-analysis of 27 studies indicated lower flexion moments in the injured limb during walking, stair ascent and descent compared to the contralateral limb. The studies included in the systematic review and meta-analysis of this thesis included participants from 2 months to 6 years following surgery, with overall results indicating partial recovery of knee flexion moments. In addition, inspection of the forest plots indicated a pattern of increase in flexion moments with time from 6 months to 6 years compared to the contralateral limb during stair ascent and descent. However, participants in the cross-sectional study (Chapter 6) were from 2 to 10 years following surgery (mean 4.7 years) and this showed that the moments continue to be lower, hence suboptimal level of joint loading, which may persist for up to 10 years.

Findings regarding the magnitude of the adduction moment in the cross-sectional study (Chapter 6) were similar to the systematic review during the stair ascent (Chapter 3). Inspection of the forest plots (Chapter 3, Figure 3.6 and 3.7) indicated that the knee adduction moment may increase over time on the injured side compared to the Control group during walking. However, no differences in the moments were found in the analysis in Chapter 6 which included participants up to 10 years following surgery. The systematic review (Chapter 3)(Kaur et al., 2016) showed that there were no differences in the knee adduction moments on the injured side compared to the contralateral side and the Control group following the reconstruction. Findings of Chapter 3 may be explained by the included study (Zabala et al., 2013) in the review, as the participants included were from 22-34 months following ACLR. Lower moments during the initial years may be due to hesitancy in weight bearing. Other studies in the review indicated no differences in the magnitude of the adduction moment, which are in agreement with our study results. Overall, taking together the results from Chapter 6 and Chapter 3, joint loading is lower in the injured limb compared to the contralateral limb. Lower joint loading is associated with early knee osteoarthritis 5 years following ACL injury (Wellsandt et al., 2016). Those authors speculated the reduced level of joint loading may be an indicator for risk for early onset and progression of osteoarthritis participants with ACLR, rather than the increased loading in the injured knee years after surgery (Wellsandt et al., 2016). Concurrently, increased loading is also detrimental to articular cartilage. Higher adduction moment was found in patients with knee osteoarthritis (Astephen et al., 2008).

There are few plausible explanations for the lower level of joint loading in participants with ACLR. Joint moments (external knee flexion moment) have been associated the muscle strength (Lewek et al., 2002; Schmitt et al., 2015), thus lower strength can lead to the lower joint loading (Chapter 7). However, other factors need to be considered. For instance, fear of injury, lower confidence levels (Chapter 5), and hesitation during weight bearing seen in this cohort of participants, could be responsible for the lower joint loading. Moreover, the changes in the central nervous system have been recently reported following ACL injury and reconstruction (Grooms et al., 2017). Neuroplasticity in the central nervous system was expressed by increased activation in the contralateral motor cortex, and diminished activation in the ipsilateral motor cortex and cerebellum compared to healthy controls following ACLR (Grooms et al., 2017). Reduced knee joint loading following ACLR may be associated with the neuroplasticity in the central nervous system. The mechanical model of degeneration is generally thought to be a cause of early onset post-traumatic osteoarthritis (Andriacchi et al., 2004); however, findings from this thesis have shown that there are additional psychosocial aspects which might contribute to an unfavourable outcomes to the ACLR surgery. Psychological aspects of the injury and surgery, as indicated in Chapter 5, may affect not only the loading at the knee but may also impact the participants' quality of life and participation in sports.

Suboptimal level of joint loading is deleterious to the joint health. Lower moments along with abnormal kinematics can lead to a shift in the joint loads to the areas of the cartilage which may not be conditioned to the high level of loading (Chaudhari, Briant, Bevill, Koo, & Andriacchi, 2008). Concurrently, lower muscle strength can affect the physical performance in participants with ACLR (Schmitt et al., 2012) and has been considered as a risk factor for the onset and progression of osteoarthritis (Keays et al., 2007; Tourville et al., 2014). This indicates the need to restore the optimal level of joint loading and muscle strength. Therefore, the physical and muscle-related impairments could be the marker of osteoarthritis in participants with ACLR.

Findings from this thesis and the literature suggest that patients with ACLR present with psychological impairments that impact on their ability to engage with sports at the same level prior to injury. The results of the mixed-method study (Chapter 5) indicate the impact of psychological factors on the overall participants’ confidence during sports and therefore impact the overall outcomes of the ACLR (Christino et al., 2016). Fear of injury and lower confidence is a hindrance to participation in sports and recreational activities, and can be considered to be the result of an adaptive protective behaviour (Brewer, Cornelius, Stephan, & Van Raalte, 2010) and other sensory-motor changes in the brain (Grooms et al., 2017). Psychological aspects of the injury, such as the participants’ struggle through the rehabilitation to attain the desired physical milestones and the emotional distress that accompanies this, have been highlighted previously (Scott et al., 2017).

Strategies to address the fear of re-injury such as behavioural cognitive therapy or mental-imagery techniques, have been reported to enhance the psychological and physical aspects of recovery during the early stages following surgery (Cupal & Brewer, 2001; Magyar & Chase, 1996). A previous study has indicated that physiotherapists are aware of the psychological aspects of the rehabilitation following ACLR (Von Aesch et al., 2016). However, the support provided by the health professional to deal with the psychological issues may not be sufficient, as indicated by participants’ struggle with the psychological issues in the longer-term.

Biomechanical and psychological impairments are equally influencing the quality of life in this group of participants (KOOS QOL scores, Chapter 4). These, along with the joint damage sustained at the time of injury (Culvenor et al., 2015), and the influence of inflammatory factors up to 3 years after the surgery, can potentially lead to post-traumatic osteoarthritis.

8.4 Implications for clinical practice

The studies reported in this thesis add to the existing body of knowledge by identifying the physical and psychological impairments in the longer-term. Based on the biopsychosocial approach and following the ICF model of the WHO, management of joint injuries may need an extensive approach (Quinn et al., 2012).

8.4.1 Optimising the knee moments following ACLR

Overall, reduced flexion moments indicate altered joint loading in the long-term following ACLR. These changes are likely to be associated with quadriceps weakness (Shelburne et al., 2006) and various neurophysiological mechanisms (Barret, 1991; Urbach et al., 2001; Urbach et al., 2000), and are potentially associated with risk of early onset joint degeneration (Roos et al., 1995; Roos et al., 2005) due to suboptimal joint loading during functional tasks such as walking, running, and stair navigation (Knoll et al., 2004). Altered kinematics along with reduced flexion moments may significantly change the stress distribution within the cartilage and initiate a degenerative process (Setton et al., 1999). Athletes with better physical performance at 6 months following ACLR appear to demonstrate less asymmetrical gait patterns compared to those that did not pass functional return to play criteria (Di Stasi et al., 2013). It thus appears to be important to include assessment of potential gait asymmetries following ACLR in decision making for readiness for rehabilitation progression and return to sports (Di Stasi et al., 2013; Myer et al., 2008). While small differences in walking may not be detectable on clinical examination, these may be more evident during high knee loading activities, such as stair ascent/descent, and running (Myer et al., 2008) and jumping (Paterno et al., 2007). The findings of movement and loading asymmetries in this thesis indicate that it may be important to continue with the exercise programme focusing on strength, neuromuscular control and proprioception even after the rehabilitation period is over. Based on findings from this thesis, clinicians, physiotherapists, sports doctors should consider the presence of knee loading asymmetries.

8.4.2 Restoring knee moments symmetry

This thesis contributes to the literature by adding that physical and mental impairments may persist in the long-term in patients with ACLR. There are differences in flexion moments in the injured and contralateral limb in participants with ACLR. Such differences are a risk factor for the re-injury on both the ipsilateral and contralateral side in the short-term (Paterno et al., 2010), and a risk factor for osteoarthritis in the long-term (Ajuied et al., 2014). However, to date, there is no rehabilitation program that addresses these residual impairments following ACLR in the longer-term. Participants suffer from residual muscle and biomechanical impairments, and only a few contact health professionals in the longer-term, as it was discovered in the mixed-method study (Chapter 5). In the New Zealand context, ACC usually funds surgery and rehabilitation. Rehabilitation is usually limited to 16 treatments, with the possibility of extending it depending on the progress of the individual and outcomes during rehabilitation. The number of physiotherapy sessions undertaken by participants of this study ranged from 1 to 27, based on information provided by ACC. However, it is not known how many patients access health care in the longer-term for their knee-related impairments across New Zealand.

The findings of this thesis, particularly the pattern of lower knee flexion moment and muscle strength, are similar to those seen in patients with osteoarthritis (Astephen et al., 2008), with the exception of higher adduction moments. Moment asymmetry and lower muscle strength is related to joint space narrowing and osteoarthritic changes in the knee joint in participants with ACLR (Keays et al., 2007; Tourville et al., 2014). Thus, a partial similarity in the movement pattern in participants with ACLR and osteoarthritis exists years before the onset of the symptoms. Therefore, it is important to restore the moment symmetry in these participants.

The statistically significant association of concentric quadriceps muscle strength with the knee flexion moment during stair ascent indicates that quadriceps concentric muscle strengthening exercises may be employed to restore the moments in the sagittal plane. This gives future direction for further studies. There was increase in the flexion moment in women. This indicates the need to carefully execute the rehabilitation in women to optimally restore the joint loading and not to overload the joints, which may be detrimental for joint health. The differences in the gait pattern among women and men have been found in previous studies as well (Asaeda et al., 2017), and this difference may explain the higher incidence of women of developing primary osteoarthritis. In women participants with ACLR, emphasis should be placed on restoring and maintaining the thigh muscle strength.

8.4.3 Need for an extended rehabilitation and the self-management of knee health

The ACLR affects the quality of life and levels of confidence among the participants in the longer-term. Participants with ACLR need to be followed-up beyond the rehabilitation period to address their concerns related to muscle strength, physical performance, low confidence in sports, pain, and other knee-related symptoms. Restoration of muscular strength is important for optimal joint function; therefore, future research is needed to develop an exercise protocol to address the muscular deficits in the long-term impairments. Participants should be encouraged to maintain their muscle strength.

An in-depth understanding of participants' concerns and experiences of the outcomes of ACLR highlighted the factors relating to fear of re-injury, reduced confidence in the injured limb during sports, hesitancy in weight bearing on the injured side and participants' daily struggles related to the regular activities of daily life. The presence of physical and psychological impairments indicate that an extended rehabilitation, addressing both physical impairments and psychological responses, may be needed. Participants were aware of the residual impairments in their knee and the influence of those impairments on the knee during sports-related activities. Also, participants were aware that the fear of re-injury may be related to the deficits in the muscle strength leading to hesitancy in fully engaging during sports activities. These patients need additional support aiming to restore the knee function, reduce the fear of re-injury and boost their confidence in the knee during sports. Cognitive behavioural therapy may be one helpful technique for these patients (Cupal & Brewer, 2001). Other strategies such as mental imagery techniques are suggested for those struggling with fear of re-injury (Magyar & Chase, 1996). Other minor concerns, such as knee pain and soreness following the strenuous exercises, need the attention of the health professional as well.

The findings of this thesis suggest that a broader approach may be helpful for participants with ACLR in the longer-term. This longer-term care plan should include a protocol emphasising muscle strengthening along with the psychological aspects of the injury to deal with the persistent fear of re-injury in those who are unable to engage fully in sports. Self-management of the knee condition needs to be incorporated in the long-term. Good response to a web-based intervention has been found in another study, exploring the self-management of acute or chronic knee conditions in adults (Button, Nicholas, Busse, Collins, & Spasić, 2018). In that study, web-based intervention consisting of a complex intervention combining information resources, exercise videos, personalised exercise plans and remote contact with a physiotherapist alongside face-to-face treatment was administered. It was reported to be acceptable, easy to use and appropriate for a wide spectrum of patients. Similar web-based programs may be defined and administered in this cohort of patients in the long-term. Also, strategies to improve the self-efficacy in the long-term for patients needs to be developed and incorporated. Short-term postoperative self-efficacy was found to be a better predictor of long-term outcome after total hip or knee arthroplasty in a cohort of 103 patients following surgery (Akker-Scheek, Stevens, Groothoff, Bulstra, & Zijlstra, 2007). That study recommended interventions focusing on enhancing short-term postoperative rather than preoperative self-efficacy. Similar strategies may need to be followed for individuals with ACLR.

8.4.4 Need of patient education

Patient education may be beneficial, as they would be aware of the possibility of impairments following ACLR, and therefore could take control and improve self-efficacy. Participants indicated that they wished to know about the future of the knee in the long-term. Patient education, focusing on identifying the presence of fear of re-injury and their predisposition to the early onset of osteoarthritis, is required in early stages of rehabilitation process. Patients need to be educated regarding the protective role of muscle strength in the prevention of the osteoarthritis.

8.4.5 Tool for assessment

Flexion moments were associated with the concentric quadriceps muscle strength during stair ascent (Chapter 7). Quadriceps muscle deficits may thus be an indicator of reduced loading. Therefore, assessing the concentric quadriceps muscle strength could be useful as an assessment tool to assess residual impairments in participants with ACLR.

Participants in the research described in Chapter 5 revealed problems with stair ascent and descent. Moment asymmetry was found during stair ascent and descent activities in this cohort of participants (Chapter 6). Some of the studies in the literature did not report the deficits in moments or angles during walking activity (Hall et al., 2012; Webster, McClelland, et al., 2012), which may be due to walking as an activity with a lower level of joint loading than the stairs. Negotiating stairs involves a higher level of joint loading, and therefore can be used as the task for analysis in future studies.

8.5 **Strengths of this thesis**

8.5.1 Sequential design of studies

The sequential design of the studies aimed to investigate different aspects of the overarching research question in a logical way. Dependent variables for the quantitative study (Chapter 6) were finalised based on the findings of the systematic review and meta-analysis (Chapter 3) and it also directed the research process to compare the moments and angles in participants with ACLR to the Control group in the longer-term following surgery. Also, the association of the knee flexion moment with the concentric quadriceps muscle strength pointed towards a way of the restoring the knee flexion moment (Chapter 7), although this needs to be explored further in future studies.

8.5.2 Mixed method approach

A strength of this study was that a biopsychosocial approach could be followed by using a mixed-method design across the studies, enriching the understanding of the research topic. To answer the research question in more depth, the quantitative and qualitative research paradigms were combined. This approach helped to understand not only the physical impairments of participants with ACLR, but also their concerns, beliefs and fears associated with their health.

Comparing the patient-reported outcomes in Chapter 4 between groups indicated lower confidence during sports and quality of life in participants with ACLR compared to the Control group. These findings were deepened through the mixed-method study (Chapter 5) which focused on the participants' concerns. Using mixed-methods in the field of musculoskeletal physiotherapy practice is not common, so its use in this thesis was innovative, and provided a deeper understanding of the phenomenon and generated the resulting conceptual model of the outcomes of ACLR.

8.5.3 Data analysis

The statistical methods used in Chapter 4 and 6 helped us to explore the inter-limb differences within and between the groups among the participants with ACLR compared to the Control group using the repeated measure ANOVA. Regression analysis, the statistical test used in Chapter 7, is known to be a robust test in terms of predicting the relationships between the variables. The thematic analysis used for the analysis of interview data in the mixed-method study (Chapter 5) is one of the most robust methods used in this research paradigm.

8.5.4 Contribution to the literature

Previous studies exploring the outcomes of ACLR have focused on the short-term outcomes of the surgery, and only few have included a combination of the biomechanical and patient perspectives of the surgery. The systematic review and meta-analysis (Chapter 3) provided the time course of the recovery of angles and moments following surgery and provided the subgroup analysis during different tasks. The mixed-method study (Chapter 5) indicated that fear of injury continues to persist for a long time following ACLR, and this may impact differently on the execution of the movement. This thesis explored the long-term outcomes following the surgery, and explored muscle strength, physical performance, knee laxity, and patient-reported outcomes related to the surgery, along with the biomechanical analysis during stair ascent and descent. This approach helped in the study of the outcomes of surgery considering the person as ‘whole’, and enabled an understanding of the reasons behind the psychological concerns. The psychological concerns of these individuals can affect physical performance and participation in sport and exercise. It can have implications for the athletes, coaches, and parents regarding injury, rehabilitation, and career transition following ACL injury and surgery.

8.6 **Limitations**

Although specific limitations for each study have been already discussed in the previous chapters, this section highlights the limitations in the context of the whole thesis.

8.6.1 Knee-related impairments only

Studies were designed to explore the thigh muscle strength and knee moments only, whereas there could be strength impairments present at the hip and ankle which were not explored. Only knee-related moments were studied in this thesis; however, there could be compensations from the other joints such as hip and ankle, and also from the trunk, influencing the overall moments. However, these were not explored in this thesis as the focus was on the knee-related impairments.

The thesis analysed the stair ascent and descent as the functional task for performed by participants. Although it is a high loading activity compared to walking, a more detailed level of understanding could have been gained from the analysis of additional activities such as vertical jump and running.

8.6.2 Recruitment of participants with 10-20 years post-reconstruction

Sample size estimations indicated the need to recruit 26 participants with ACLR 10-20 years following surgery. Recruiting patients 10-20 years following surgery was a challenge. We could not recruit more than 9 participants in this group, despite extensive advertising in the Masters' games, including sports and golf clubs, and social media. It is possible that priorities in life in terms of family and occupational commitments have changed in the 10 to 20 years following surgery, with possibly greater acceptance of the post-surgery limitations, resulting in less interest by such patients to participate in this research study. Interpretation of the results of the regression analysis needs to consider the small number of participants more than 10 years following ACLR. It is possible that a Type 2 error occurred: a larger group of participants needs to be explored to confirm whether knee moments change over time following surgery in the longer-term.

8.6.3 Lack of imaging

Biomechanical and physical impairments were analysed in this thesis, which are known to be predisposing factors for osteoarthritis. However, the presence or absence of knee osteoarthritis was not confirmed radiologically in this group of participants, which could have provided definite association between the physical impairments and the onset and progression of osteoarthritis in this group of participants.

8.6.4 Surgical factors

Outcome of the surgery depends on many factors related to that surgery, such as the positioning of the tunnel, type of graft, time between injury and surgery, and type of rehabilitation. For instance, muscle strength deficits may be related to the type of graft (Dauty et al., 2005; Xergia et al., 2011). As participants were recruited from the community, groupings were not based on the type of graft. This could have led to dilution of the results in the muscle strength-related outcomes in this thesis.

8.7 Recommendations for future research

8.7.1 Analysis of data using statistical parametric mapping

Only discrete variables were used in all planes to find the within- and between-group differences. However, there are chances that differences are more pronounced among groups at different times compared to the peak moments and angles. Biomechanical data collected for this PhD project can be revisited in the future for performing a statistical parametric mapping (SPM). This method uses a 1-dimensional (1D) continuous vector trajectory that changes in time or space (Pataky, 2012; Sole, Pataky, Tengman, & Häger, 2017). Random Field Theory is used to make probabilistic conclusions based on the random behaviour of that 1-dimensional observational unit. The SPM could be applied to test differences for knee trajectories during stair ascent and descent to explore the differences in knee trajectories.

8.7.2 *In depth exploration of knee flexion moment and quadriceps muscle strength*

Concentric quadriceps muscle strength and the sex of the participants were associated with the knee flexion moment. This association should be explored further in future studies by determining the improvement in the flexion moment with quadriceps strengthening in participants with ACLR. If improving the quadriceps muscle strength leads to an optimised knee flexion moment, then this can be helpful in the development of an exercise protocol to optimise loading. Later on, those exercises can be recommended to be included in the rehabilitation following surgery if the protocol is successful to optimise the moment asymmetry.

The regression analysis indicated that women participants had higher weight- and height-normalised flexion moments compared to men. This needs to be confirmed (or disputed) in a larger study as the current study did not have the power to determine differences for knee moments following ACLR between men and women.

8.7.3 *Patient education and exercises for long-term management*

Participants were concerned about developing osteoarthritis, and about having to undergo a knee replacement on the injured knee; they continued to suffer from a fear of re-injury and had lower confidence during sports. Patients should be guided by the health professionals by explaining the exact risk-related percentage for the predisposition to osteoarthritis, along with the preventive strategies, so that the participants are knowledgeable about the maintenance of their knee health.

Participants with ACLR have shown the need for psychological support during rehabilitation due to the challenging and unexpected nature of the ACL injury and the rehabilitation which follows (Scott et al., 2017). In another study, physiotherapists have suggested providing psychological support during rehabilitation (Von Aesch et al., 2016). Some psychological support from health professionals needs to be continued, along with incorporating a biopsychosocial approach and patient education about management strategies. Persistence of the fear of injury in the long-term should be managed by developing the right exercise protocols challenging their fears, along with ensuring that their knee can sustain those difficult movements to regain their confidence. A previous study has indicated that psychological factors may constitute an underappreciated effect on surgical outcomes after ACLR (Christino et al., 2016). Therefore, psychological interventions aimed at increasing self-esteem, locus of control, self-efficacy, and confidence could help improve the surgical outcomes (Christino et al., 2016).

8.8 **Conclusions**

Five studies were undertaken to address the aims of the thesis. Physical impairments related to the muscle strength deficits and lower knee flexion moment persist in the longer-term, which may be responsible for suboptimal knee joint health. Previously, the emphasis has been on the mechanical model of joint loading being responsible for degeneration. It is likely that it is the combination of biomechanical, physical and psychosocial factors which are responsible for the short and long-term outcomes following the surgery. Lower confidence in the knee and fear of injury also persist in participants 2-10 years following surgery, which may affect their sports-related performance. These physical impairments and psychosocial factors may play a significant role in the overall outcome and burden of ACLR.

References

Access Economics for Arthritis New Zealand, (2010). The economic cost of Arthritis in New Zealand in 2010.

Ageberg, E., Forssblad, M., Herbertsson, P., & Roos, E. M. (2010). Sex differences in patient-reported outcomes after anterior cruciate ligament reconstruction: data from the Swedish knee ligament register. *The American Journal of Sports Medicine, 38*(7), 1334-1342.

Aglietti, P., Buzzi, R., Giron, F., Simeone, A., & Zaccherotti, G. (1997). Arthroscopic-assisted anterior cruciate ligament reconstruction with the central third patellar tendon A 5–8-year follow-up. *Knee Surgery, Sports Traumatology, Arthroscopy, 5*(3), 138-144.

Ahldén, M., Kartus, J., Ejerhed, L., Karlsson, J., & Sernert, N. (2009). Knee laxity measurements after anterior cruciate ligament reconstruction, using either bone–patellar–tendon–bone or hamstring tendon autografts, with special emphasis on comparison over time. *Knee Surgery, Sports Traumatology, Arthroscopy, 17*(9), 1117-1124.

Åhlén, M., Roshani, L., Lidén, M., Struglics, A., Rostgård-Christensen, L., & Kartus, J. (2015). Inflammatory cytokines and biomarkers of cartilage metabolism 8 years after anterior cruciate ligament reconstruction: results from operated and contralateral knees. *The American Journal of Sports Medicine, 43*(6), 1460-1466.

Ajuied, A., Wong, F., Smith, C., Norris, M., Earnshaw, P., Back, D., & Davies, A. (2014). Anterior cruciate ligament injury and radiologic progression of knee osteoarthritis: a systematic review and meta-analysis. *The American Journal of Sports Medicine, 42*(9), 2242-2252.

Aksekili, M., E., Fidan, F., Alkan, B. M., Alemdar, A., Aksekili, H., & Ardıçoğlu, Ö. (2016). Quality of life in knee osteoarthritis; correlation with clinical measures and the knee injury and osteoarthritis outcome score. *Acta Medica Anatolia, 4*(1), 1-7.

Amis, A., & Dawkins, G. (1991). Functional anatomy of the anterior cruciate ligament. Fibre bundle actions related to ligament replacements and injuries. *Bone & Joint Journal, 73*(2), 260-267.

Anderson, A. F., & Lipscomb, A. B. (1989). Preoperative instrumented testing of anterior and posterior knee laxity. *The American Journal of Sports Medicine, 17*(3), 387-392.

Anderson, D. D., Chubinskaya, S., Guilak, F., Martin, J. A., Oegema, T. R., Olson, S. A., & Buckwalter, J. A. (2011). Post-traumatic osteoarthritis: Improved understanding and opportunities for early intervention. *Journal of Orthopaedic Research, 29*(6), 802-809.

Andriacchi, T., Mündermann, A., Smith, R. L., Alexander, E., Dyrby, C., & Koo, S. (2004). A Framework for the in Vivo Pathomechanics of Osteoarthritis at the Knee. *Annals of Biomedical Engineering, 32*(3), 447-457.

Andriacchi, T., & Strickland, A. (1985). Gait analysis as a tool to assess joint kinetics *Biomechanics of normal and pathological human articulating joints*, 83-102: Springer.

Andriacchi, T. P. (1990). Dynamics of pathological motion: applied to the anterior cruciate deficient knee. *Journal of Biomechanics, 23*, 99-105.

Andriacchi, T. P., Briant, P. L., Bevill, S. L., & Koo, S. (2006). Rotational changes at the knee after ACL injury cause cartilage thinning. *Clinical Orthopaedics and Related Research* (442), 39-44.

Andriacchi, T. P., & Dyrby, C. O. (2005). Interactions between kinematics and loading during walking for the normal and ACL deficient knee. *Journal of Biomechanics, 38*(2), 293-298.

Andriacchi, T. P., Favre, J., Erhart-Hledik, J. C., & Chu, C. R. (2015). A systems view of risk factors for knee osteoarthritis reveals insights into the pathogenesis of the disease. *Annals of Biomedical Engineering, 43*(2), 376-387.

Andriacchi, T. P., Koo, S., & Scanlan, S. F. (2009). Gait mechanics influence healthy cartilage morphology and osteoarthritis of the knee. *The Journal of Bone and Joint Surgery. American volume, 91 Suppl 1*, 95-101.

Andriacchi, T. P., & Mündermann, A. (2006). The role of ambulatory mechanics in the initiation and progression of knee osteoarthritis. *Current Opinion in Rheumatology, 18*(5), 514-518.

Ardern, C. L. (2015). Anterior cruciate ligament reconstruction—not exactly a one-way ticket back to the preinjury level: a review of contextual factors affecting return to sport after surgery. *Sports Health, 7*(3), 224-230.

Ardern, C. L., Österberg, A., Sonesson, S., Gauffin, H., Webster, K. E., & Kvist, J. (2016). Satisfaction with knee function after primary anterior cruciate ligament reconstruction is associated with self-efficacy, quality of life, and returning to the preinjury physical activity. *Arthroscopy: The Journal of Arthroscopic & Related Surgery, 32*(8), 1631-1638. e1633.

Ardern, C. L., Taylor, N. F., Feller, J. A., & Webster, K. E. (2012). Fear of re-injury in people who have returned to sport following anterior cruciate ligament reconstruction surgery. *Journal of Science and Medicine in Sports, 15*(6), 488-495.

Ardern, C. L., Taylor, N. F., Feller, J. A., & Webster, K. E. (2014). Fifty-five per cent return to competitive sport following anterior cruciate ligament reconstruction surgery: an updated systematic review and meta-analysis including aspects of physical functioning and contextual factors. *British Journal of Sports Medicine, 48*(21), 1543-1552.

Ardern, C. L., Taylor, N. F., Feller, J. A., Whitehead, T. S., & Webster, K. E. (2013). Psychological responses matter in returning to preinjury level of sport after anterior cruciate ligament reconstruction surgery. *American Journal of Sports Medicine, 41*(7), 1549-1558.

Arneja, S., & Leith, J. (2009). Validity of the KT-1000 knee ligament arthrometer. *Journal of Orthopaedic Surgery, 17*(1), 77-79.

Asaeda, M., Deie, M., Fujita, N., Kono, Y., Terai, C., Kuwahara, W., Watanabe, Hiroaki, K.,Adachi, H., Nobuo, A., Sunagawa, T. (2017). Gender differences in the restoration of knee joint biomechanics during gait after anterior cruciate ligament reconstruction. *Knee*, 24(2), 280-288.

Astephen, J. L., Deluzio, K. J., Caldwell, G. E., Dunbar, M. J., & Hubley-Kozey, C. L. (2008). Gait and neuromuscular pattern changes are associated with differences in knee osteoarthritis severity levels. *Journal of Biomechanics, 41*(4), 868-876.

Baker, S. E., Edwards, R., & Doidge, M. (2012). How many qualitative interviews is enough?: Expert voices and early career reflections on sampling and cases in qualitative research. Retrueved from {http://eprints.brighton.ac.uk/id/eprint/11632}

Barcellona, M. G., Christopher, T., & Morrissey, M. C. (2013). Bench testing of a knee joint arthrometer. *Orthopedics, 36*(8), e1000-e1006.

Barret, D. S. (1991). Proprioception and function after anterior cruciate reconstruction. *Journal of Bone and Joint Surgery - Series B, 73*(5), 833-837.

Barton, C. J., Lack, S., Malliaras, P., & Morrissey, D. (2013). Gluteal muscle activity and patellofemoral pain syndrome: a systematic review. *British Journal of Sports Medicine, 47*(4), 207-214.

Baumgart, C., Hoppe, M. W., & Freiwald, J. (2017). Phase-Specific ground reaction force analyses of bilateral and unilateral jumps in patients with ACL reconstruction. *Orthopaedic Journal of Sports Medicine*, *5*(6), 2325967117710912.

Bekkers, J., De Windt, T. S., Raijmakers, N., Dhert, W., & Saris, D. (2009). Validation of the Knee Injury and Osteoarthritis Outcome Score (KOOS) for the treatment of focal cartilage lesions. *Osteoarthritis and Cartilage,* 17(11), 1434-1439.

Benedetti, M. G., Agostini, V., Knaflitz, M., & Bonato, P. (2012). Muscle activation patterns during level walking and stair ambulation *Applications of EMG in clinical and sports medicine: InTech*. Jan. 2012, Chap. 8.

Bennell, K. L., Kyriakides, M., Metcalf, B., Egerton, T., Wrigley, T. V., Hodges, P. W., Ageberg, E. (2014). Neuromuscular versus quadriceps strengthening exercise in patients with medial knee osteoarthritis and varus malalignment: a randomized controlled trial. *Arthritis & Rheumatology, 66*(4), 950-959.

Berchuck, M., Andriacchi, T. P., Bach, B. R., & Reider, B. (1990). Gait adaptations by patients who have a deficient anterior cruciate ligament. *Journal of Bone and Joint Surgery, 72*(6), 871-877.

Besier, T. F., Sturnieks, D. L., Alderson, J. A., & Lloyd, D. G. (2003). Repeatability of gait data using a functional hip joint centre and a mean helical knee axis. *Journal of Biomechanics*, *36*(8), 1159-1168.

Beynnon, B. D., Uh, B. S., Johnson, R. J., Abate, J. A., Nichols, C. E., Fleming, B. C., . Roos, H. (2005). Rehabilitation after anterior cruciate ligament reconstruction: a prospective, randomized, double-blind comparison of programs administered over 2 different time intervals. *American Journal of Sports Medicine, 33*(3), 347-359.

Bobbert, M. (2001). Dependence of human squat jump performance on the series elastic compliance of the triceps surae: a simulation study. *Journal of Experimental Biology, 204*(3), 533-542.

Bodkin, S., Goetschius, J., Hertel, J., & Hart, J. (2017). Relationships of muscle function and subjective knee function in patients after ACL reconstruction. *Orthopaedic Journal of Sports Medicine, 5*(7), 2325967117719041.

Bonfim, T. R., Paccola, C. A. J., & Barela, J. A. (2003). Proprioceptive and behavior impairments in individuals with anterior cruciate ligament reconstructed knees. *Archives of Physical Medicine and Rehabilitation*, *84*(8), 1217-1223.

Borsa, P. A., Lephart, S. M., & Irrgang, J. J. (1998). Comparison of performance-based and patient-reported measures of function in anterior-cruciate-ligament-deficient individuals. *Journal of Orthopaedic & Sports Physical Therapy, 28*(6), 392-399.

Brewer, B. W., Cornelius, A. E., Stephan, Y., & Van Raalte, J. (2010). Self-protective changes in athletic identity following anterior cruciate ligament reconstruction. *Psychology of Sport and Exercise, 11*(1), 1-5.

Briggs, K. K., Lysholm, J., Tegner, Y., Rodkey, W. G., Kocher, M. S., & Steadman, J. R. (2009). The reliability, validity, and responsiveness of the lysholm score and tegner activity scale for anterior cruciate ligament injuries of the knee. *American Journal of Sports Medicine, 37*(5), 890-897.

Brooks, P. M. (2002). Impact of osteoarthritis on individuals and society: how much disability? Social consequences and health economic implications. *Current Opinion in Rheumatology*, *14*(5), 573-577.

Brophy, R. H., Zeltser, D., Wright, R. W., & Flanigan, D. (2010). Anterior cruciate ligament reconstruction and concomitant articular cartilage injury: incidence and treatment. *Arthroscopy : the journal of arthroscopic & related surgery : official publication of the Arthroscopy Association of North America and the International Arthroscopy Association, 26*(1), 112-120.

Brown, T. N., Palmieri-Smith, R. M., & McLean, S. G. (2009). Sex and limb differences in hip and knee kinematics and kinetics during anticipated and unanticipated jump landings:

Implications for anterior cruciate ligament injury. *British Journal of Sports Medicine, 43*(13), 1049-1056.

Buckwalter, J. (2002). Articular cartilage injuries. *Clinical Orthopaedics and Related Research, 402*, 21-37.

Buckwalter, J. A. (1992). Mechanical injuries of articular cartilage. *The Iowa Orthopaedic Journa*l, *12*, 50.

Bulgheroni, P., Bulgheroni, M. V., Andrini, L., Guffanti, P., & Giughello, A. (1997). Gait patterns after anterior cruciate ligament reconstruction. *Knee Surgery Sports Traumatology Arthroscopy, 5*(1), 14-21.

Bush-Joseph, C. A., Hurwitz, D. E., Patel, R. R., Bahrani, Y., Garretson, R., Bach, B. R., Jr., & Andriacchi, T. P. (2001). Dynamic function after anterior cruciate ligament reconstruction with autologous patellar tendon. *American Journal of Sports Medicine, 29*(1), 36-41.

Butler, R. J., Minick, K. I., Ferber, R., & Underwood, F. (2009). Gait mechanics after ACL reconstruction: Implications for the early onset of knee osteoarthritis. *British Journal of Sports Medine, 43*(5), 366-370.

Button, K., Roos, P. E., & van Deursen, R. W. (2014). Activity progression for anterior cruciate ligament injured individuals. *Clin Biomech (Bristol, Avon), 29*(2), 206-212.

Calder, K. M., Acker, S. M., Arora, N., Beattie, K. A., Callaghan, J. P., Adachi, J. D., & Maly, M. R. (2014). Knee power is an important parameter in understanding medial knee joint load in knee osteoarthritis. *Arthritis Care & Research, 66*(5), 687-694.

Cappozzo, A. (1984). Gait analysis methodology. *Human movement science, 3*(1), 27-50.

Carr, A. J., Gibson, B., & Robinson, P. G. (2001). Is quality of life determined by expectations or experience? *British Medical Journal, 322*(7296), 1240.

Castanharo, R., da Luz, B. S., Bitar, A. C., D'Elia, C. O., Castropil, W., & Duarte, M. (2011). Males still have limb asymmetries in multijoint movement tasks more than 2 years following anterior cruciate ligament reconstruction. *Journal of Orthopaedic Science, 16*(5), 531-535.

Cattano, N., Barbe, M., Massicotte, V., Sitler, M., Balasubramanian, E., Tierney, R., & Driban, J. (2013). Joint trauma initiates knee osteoarthritis through biochemical and biomechanical processes and interactions. *Osteoarthritis Musculoskeletal Medicine, 1*(1), 3.

Chaudhari, A. M., Briant, P. L., Bevill, S. L., Koo, S., & Andriacchi, T. P. (2008). Knee kinematics, cartilage morphology, and osteoarthritis after ACL injury. *Medine and Science in Sports and Exercise, 40*(2), 215-222.

Chehab, E. F., Favre, J., Erhart-Hledik, J. C., & Andriacchi, T. P. (2014). Baseline knee adduction and flexion moments during walking are both associated with 5 year cartilage changes in patients with medial knee osteoarthritis. *Osteoarthritis and Cartilage, 22*(11), 1833-1839.

Christino, M. A., Fleming, B. C., Machan, J. T., & Shalvoy, R. M. (2016). Psychological factors associated with anterior cruciate ligament reconstruction recovery. *Orthopaedic Journal of Sports Medicine, 4*(3), 2325967116638341.

Cohen, J. (1988). Statistical power analysis for behavioural sciences. Hillsdale, NJ: Lawrence Eribaum Associates. *Inc.:[sn]*.

Collins, N. J., Misra, D., Felson, D. T., Crossley, K. M., & Roos, E. M. (2011). Measures of knee function: International Knee Documentation Committee (IKDC) Subjective Knee Evaluation Form, Knee Injury and Osteoarthritis Outcome Score (KOOS), Knee Injury and Osteoarthritis Outcome Score Physical Function Short Form (KOOS-PS), Knee Outcome Survey Activities of Daily Living Scale (KOS-ADL), Lysholm Knee Scoring Scale, Oxford Knee Score (OKS), Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC), Activity Rating Scale (ARS), and Tegner Activity Score (TAS). *Arthritis care & Research, 63*(S11), S208-S228.

Courtney, C. A., & Rine, R. M. (2006). Central somatosensory changes associated with improved dynamic balance in subjects with anterior cruciate ligament deficiency. *Gait and posture, 24*(2), 190-195.

Culvenor, A. G., Collins, N. J., Guermazi, A., Cook, J. L., Vicenzino, B., Khan, K. M., Crossley, K. M. (2015). Early knee osteoarthritis is evident one year following anterior cruciate ligament reconstruction: a magnetic resonance imaging evaluation. *Arthritis & Rheumatology, 67*(4), 946-955.

Cupal, D. D., & Brewer, B. W. (2001). Effects of relaxation and guided imagery on knee strength, reinjury anxiety, and pain following anterior cruciate ligament reconstruction. *Rehabilitation Psychology, 46*(1), 28.

Czamara, A., Markowska, I., Królikowska, A., Szopa, A., & Domagalska Szopa, M. (2015). Kinematics of rotation in joints of the lower limbs and pelvis during gait: early results—SB ACLR approach versus DB ACLR approach. *BioMed Research International, 2015*, 13.

Dalton, E. C., Pfile, K. R., Weniger, G. R., Ingersoll, C. D., Herman, D., & Hart, J. M. (2011). Neuromuscular changes after aerobic exercise in people with anterior cruciate ligament–reconstructed knees. *National Athletic Trainers' Association, Inc*. 46(5), 476-483.

Dauty, M., Tortellier, L., & Rochcongar, P. (2005). Isokinetic and anterior cruciate ligament reconstruction with hamstrings or patella tendon graft: analysis of literature. *International Journal of Sports Medicine, 26*(07), 599-606.

De Carlo, M. S., & Sell, K. E. (1997). The effects of the number and frequency of physical therapy treatments on selected outcomes of treatment in patients with anterior cruciate ligament reconstruction. *Journal of Orthopaedic & Sports Physical Therapy, 26*(6), 332-339.

Dekel, S., & Weissman, S. (1978). Joint changes after overuse and peak overloading of rabbit knees in vivo. *Acta orthopaedica Scandinavica, 49*(6), 519-528.

Delincé, P., & Ghafil, D. (2012). Anterior cruciate ligament tears: conservative or surgical treatment? A critical review of the literature. *Knee Surgery, Sports Traumatology, Arthroscopy, 20*(1), 48-61.

Denzin, N. K., & Lincoln, Y. S. (2005). Introduction: The discipline and practice of qualitative research.. Handbook of qualitative research (2nd edn)(sid. 1l32) (Thousand Oaks, CA, Sa).

Devgan, A., Magu, N., Siwach, R., Rohilla, R., & Sangwan, S. (2011). Functional outcome in athletes at five years of arthroscopic anterior cruciate ligament reconstruction. *ISRN orthopedics, 2011*. 1–6.

Di Stasi, S., Hartigan, E. H., & Snyder-Mackler, L. (2015). Sex-specific gait adaptations prior to and up to 6 months after anterior cruciate ligament reconstruction. *Journal of Orthopaedic & Sports Physical Therapy, 45*(3), 207-214.

Di Stasi, S. L., Logerstedt, D., Gardinier, E. S., & Snyder-Mackler, L. (2013). Gait patterns differ between ACL-reconstructed athletes who pass return-to-sport criteria and those who fail. *American Journal of Sports Medicine, 41*(6), 1310-1318.

Di Stasi, S. L., & Snyder-Mackler, L. (2012). The effects of neuromuscular training on the gait patterns of ACL-deficient men and women. *Clinical Biomechanics, 27*(4), 360-365.

Downs, S. H., & Black, N. (1998). The feasibility of creating a checklist for the assessment of the methodological quality both of randomised and non-randomised studies of health care interventions. *Journal of Epidemiology and Community Health, 52*(6), 377-384.

Doyle, C., Lennox, L., & Bell, D. (2013). A systematic review of evidence on the links between patient experience and clinical safety and effectiveness. *British Medical Journal Open, 3*(1), e001570.

Doyle, K., Wilson, F., & King, E. (2013). Factors which influence return to sport following anterior cruciate ligament (ACL) reconstruction surgery: a narrative review: review article. *International Sportmed Journal, 14*(3), 168-184.

EItzEn, I., Moksnes, H., Snyder-Mackler, L., & Risberg, M. A. (2010). A progressive 5-week exercise therapy program leads to significant improvement in knee function early after anterior cruciate ligament injury. *Journal of Orthopaedic & Sports Physical Therapy, 40*(11), 705-721.

Ejerhed, L., Kartus, J., Köhler, K., Sernert, N., Brandsson, S., & Karlsson, J. (2001). Preconditioning patellar tendon autografts in arthroscopic anterior cruciate ligament reconstruction: a prospective randomized study. *Knee Surgery, Sports Traumatology, Arthroscopy, 9*(1), 6-11.

Elias, A. R., Hammill, C. D., & Mizner, R. L. (2015). Changes in quadriceps and hamstring cocontraction following landing instruction in patients with anterior cruciate ligament reconstruction. *Journal of Orthopaedic & Sports Physical Therapy, 45*(4), 273-280.

EMathZone, C. v. Reference for grand mean: EMathZone, Combined variance. *[cited Accessed 7th October 2014. ; Available from: http://www.emathzone.com/tutorials/basic-statistics/combined-variance.html;* .

Epstein, R. M., & Street, R. L. (2011). The values and value of patient-centered care: *Annals Family Medicne*, (9), 100-103.

Erhart-Hledik, J. C., Chu, C. R., Asay, J. L., & Andriacchi, T. P. (2016). Gait mechanics 2 years after anterior cruciate ligament reconstruction are associated with longer-term changes in patient-reported outcomes. *Journal of Orthopaedic Research*. *35*(3), 634-640.

Ernst, G. P., Saliba, E., Diduch, D. R., Hurwitz, S. R., & Ball, D. W. (2000). Lower-extremity compensations following anterior cruciate ligament reconstruction. *Physical Therapy, 80*(3), 251-260.

Farr, J. N., Going, S. B., McKnight, P. E., Kasle, S., Cussler, E. C., & Cornett, M. (2010). Progressive resistance training improves overall physical activity levels in patients with early osteoarthritis of the knee: a randomized controlled trial. *Physical Therapy, 90*(3), 356.

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G* Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39*(2), 175-191.

Ferber, R., Osternig, L. R., Woollacott, M. H., Wasielewski, N. J., & Lee, J. H. (2002). Gait mechanics in chronic ACL deficiency and subsequent repair. *Clinical Biomechanics (Bristol, Avon), 17*(4), 274-285.

Ferrans, C. E. (2005). Definitions and conceptual models of quality of life. *Outcomes assessment in cancer: Measures, methods, and applications*, 14-30. by Lipscomb, Joseph (ed.) ; Gotay, Carolyn C. (ed.) ; Snyder, Clarie (ed.) . 14-30, Chapter xiv, 662 Pages. New York, NY, US: Cambridge University Press, 2005

Field, A. (2009). Discovering Statistics using SPSS. 3rd Edition, Sage Publications Ltd. London.

Filbay, S., Ackerman, I., Russell, T., & Crossley, K. (2016). Return to sport matters—longer-term quality of life after ACL reconstruction in people with knee difficulties. *Scandinavian Journal of Medicine & Science in Sports*, *27*(5), 514-524.

Filbay, S. R., Ackerman, I. N., Russell, T. G., Macri, E. M., & Crossley, K. M. (2014). Health-related quality of life after anterior cruciate ligament reconstruction: A systematic review. *The American Journal of Sports Medicine, 42*(5), 1247-1255.

Filbay, S. R., Crossley, K. M., & Ackerman, I. N. (2016). Activity preferences, lifestyle modifications and re-injury fears influence longer-term quality of life in people with knee symptoms following anterior cruciate ligament reconstruction: a qualitative study. *Journal of Physiotherapy, 62*(2), 103-110.

Flanigan, D. C., Everhart, J. S., Pedroza, A., Smith, T., & Kaeding, C. C. (2013). Fear of reinjury (kinesiophobia) and persistent knee symptoms are common factors for lack of return to sport after anterior cruciate ligament reconstruction. *Arthroscopy : The Journal of Arthroscopic & Related Surgery : official publication of the Arthroscopy Association of North America and the International Arthroscopy Association, 29*(8), 1322-1329.

Flosadottir, V., Roos, E. M., & Ageberg, E. (2016). Muscle function is associated with future patient-reported outcomes in young adults with ACL injury. *BMJ Open Sport & Exercise Medicine,* 2(1), e000154.

Foroughi, N., Smith, R., & Vanwanseele, B. (2009). The association of external knee adduction moment with biomechanical variables in osteoarthritis: a systematic review. *Knee, 16*(5), 303-309.

Forster, I., Warren-Smith, C., & Tew, M. (1989). Is the KT1000 knee ligament arthrometer reliable? *Bone & Joint Journal, 71*(5), 843-847.

Frobell, R. B., Roos, H., Roos, E., Le Graverand, M.-P. H., Buck, R., Tamez-Pena, J., Totterman, S., Boegard, T., Lohmander, L. (2008). The acutely ACL injured knee assessed by MRI: are large volume traumatic bone marrow lesions a sign of severe compression injury? *Osteoarthritis and Cartilage, 16*(7), 829-836.

Fugard, A. J., & Potts, H. W. (2015). Supporting thinking on sample sizes for thematic analyses: a quantitative tool. *International Journal of Social Research Methodology, 18*(6), 669-684.

Gao, B., Cordova, M. L., & Zheng, N. (2012). Three-dimensional joint kinematics of ACL-deficient and ACL-reconstructed knees during stair ascent and descent. *Human Movement Science, 31*(1), 222-235.

Gao, B., & Zheng, N. N. (2010). Alterations in three-dimensional joint kinematics of anterior cruciate ligament-deficient and-reconstructed knees during walking. *Clinical Biomechanics, 25*(3), 222-229.

Gelber, A. C., Hochberg, M. C., Mead, L. A., Wang, N.-Y., Wigley, F. M., & Klag, M. J. (2000). Joint injury in young adults and risk for subsequent knee and hip osteoarthritis. *Annals of Internal Medicine, 133*(5), 321-328.

George, E., & Eegel, L. (1980). The clinical application of the biopsychosocial model. *American Journal of Psychiatry, 137*, 535-544.

Georgoulis, A. D., Papadonikolakis, A., Papageorgiou, C. D., Mitsou, A., & Stergiou, N. (2003). Three-dimensional tibiofemoral kinematics of the anterior cruciate ligament-deficient and reconstructed knee during walking. *American Journal of Sports Medicine, 31*(1), 75-79.

Gignac, M. A., Cao, X., Ramanathan, S., White, L. M., Hurtig, M., Kunz, M., & Marks, P. H. (2015). Perceived personal importance of exercise and fears of re-injury: a longitudinal study of psychological factors related to activity after anterior cruciate ligament reconstruction. *BMC Sports Science, Medicine and Rehabilitation, 7*(1), 1.

Gianotti M., Stephen M, Humeb PA., Bunt L (2009). Incidence of anterior cruciate ligament injury and other knee ligament injuries: A national population-based study. *Journal of Science and Medicine in Sport*. *12*(6), 622-627.

Gobbi, A., & Francisco, R. (2006). Factors affecting return to sports after anterior cruciate ligament reconstruction with patellar tendon and hamstring graft: a prospective clinical investigation. *Knee Surg Sports Traumatology Arthroscopy, 14*(10), 1021-1028.

Gokeler, A., Benjaminse, A., van Eck, C. F., Webster, K. E., Schot, L., & Otten, E. (2013). Return of normal gait as an outcome measurement in acl reconstructed patients. A systematic review. *International Journal of Sports Physical Thearpy, 8*(4), 441-451.

Greene, J. C. (2007). *Mixed methods in social inquiry* (Vol. 9): John Wiley & Sons.

Griffin, T. M., & Guilak, F. (2005). The role of mechanical loading in the onset and progression of osteoarthritis. *Exercise and Sports Sciences Review, 33*(4), 195-200.

Grindem, H., Risberg, M., & Eitzen, I. (2015). Two factors that may underpin outstanding outcomes after ACL rehabilitation: *BMJ Publishing Group Ltd and British Association of Sport and Exercise Medicine.;(49), 1425*

Grindem, H., Snyder-Mackler, L., Moksnes, H., Engebretsen, L., & Risberg, M. A. (2016). Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: the Delaware-Oslo ACL cohort study. *British Journal of Sports Medicine, 50*(13), 804-808.

Grooms, D., Appelbaum, G., & Onate, J. (2015). Neuroplasticity following anterior cruciate ligament injury: a framework for visual-motor training approaches in rehabilitation. *Journal of Orthopaedic & Sports Physical Therapy, 45*(5), 381-393.

Grooms, D. R., Page, S. J., Nichols-Larsen, D. S., Chaudhari, A. M., White, S. E., & Onate, J. A. (2017). Neuroplasticity associated with anterior cruciate ligament reconstruction. *Journal of Orthopaedic & Sports Physical Therapy, 47*(3), 180-189.

Guilak, F., Fermor, B., Keefe, F. J., Kraus, V. B., Olson, S. A., Pisetsky, D. S., Setton, Lori A., Weinberg, J. B. (2004). The role of biomechanics and inflammation in cartilage injury and repair. *Clinical Orthopaedics and Related Research,(423),* 17-26.

Gustavsson, A., Neeter, C., Thomeé, P., Silbernagel, K. G., Augustsson, J., Thomeé, R., & Karlsson, J. (2006). A test battery for evaluating hop performance in patients with an ACL injury and patients who have undergone ACL reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy, 14*(8), 778-788.

Hall, M., Bennell, K., Wrigley, T., Metcalf, B., Campbell, P., Kasza, J., Paterson, KL., Hunter, DJ Hinman, R. (2017). The knee adduction moment and knee osteoarthritis symptoms:

relationships according to radiographic disease severity. *Osteoarthritis and Cartilage, 25*(1), 34-41.

Hall, M., Stevermer, C. A., & Gillette, J. C. (2012). Gait analysis post anterior cruciate ligament reconstruction: knee osteoarthritis perspective. *Gait Posture, 36*(1), 56-60.

Harkey, M., Luc, B., Golightly, Y., Thomas, A., Driban, J., Hackney, A., & Pietrosimone, B. (2015). Osteoarthritis-related biomarkers following anterior cruciate ligament injury and reconstruction: a systematic review. *Osteoarthritis and Cartilage, 23*(1), 1-12.

Hart, H. F., Collins, N. J., Ackland, D. C., & Crossley, K. M. (2015). Is impaired knee confidence related to worse kinesiophobia, symptoms, and physical function in people with knee osteoarthritis after anterior cruciate ligament reconstruction? *Journal of Science and Medicine in Sport, 18*(5), 512-517.

Hart, H. F., Culvenor, A. G., Collins, N. J., Ackland, D. C., Cowan, S. M., Machotka, Z., & Crossley, K. M. (2015). Knee kinematics and joint moments during gait following anterior cruciate ligament reconstruction: a systematic review and meta-analysis. *British Journal of Sports Medicine. 50*(10), 597-612.

Hart, J. M., Ko, J.-W. K., Konold, T., & Pietrosimione, B. (2010). Sagittal plane knee joint moments following anterior cruciate ligament injury and reconstruction: A systematic review. *Clinical Biomechanics, 25*(4), 277-283.

Hart, J. M., Pietrosimone, B., Hertel, J., & Ingersoll, C. D. (2010). Quadriceps activation following knee injuries: a systematic review. *Journal of Athletic Training, 45*(1), 87-97.

Heard, S. M., Lafave, M., Kerslake, S., Hiemstra, L., & Buchko, G. (2015). Anterior Cruciate Ligament Quality of Life (ACL-QOL) Questionnaire: Responsiveness to Change up to 2-years post ACL Reconstruction. *Arthroscopy : The Journal of Arthroscopic & Related Surgery : official publication of the Arthroscopy Association of North America and the International Arthroscopy Association*, 31(6), e5-e6.

Heijne, A., Axelsson, K., Werner, S., & Biguet, G. (2008). Rehabilitation and recovery after anterior cruciate ligament reconstruction: patients' experiences. *Scandinavian Journal of Medicine & Science in Sports cand, 18*(3), 325-335.

Herzog, W., Longino, D., & Clark, A. (2003). The role of muscles in joint adaptation and degeneration. *Langenbeck's Archives of Surgery, 388*(5), 305-315.

Hochberg, M. C., Altman, R. D., April, K. T., Benkhalti, M., Guyatt, G., McGowan, J., Towheed, T., Wells, G., Tugwell, P. (2012). American College of Rheumatology 2012 recommendations for the use of nonpharmacologic and pharmacologic therapies in osteoarthritis of the hand, hip, and knee. *Arthritis Care & Research, 64*(4), 465-474.

Hodges, P. W., & Tucker, K. (2011). Moving differently in pain: a new theory to explain the adaptation to pain. *Pain, 152*(3), S90-S98.

Hong, S. H., Choi, J.-Y., Lee, G. K., Choi, J.-A., Chung, H. W., & Kang, H. S. (2003). Grading of anterior cruciate ligament injury: diagnostic efficacy of oblique coronal magnetic resonance imaging of the knee. *Journal of Computer Assisted Tomography, 27*(5), 814-819.

Hooper, D. M., Morrissey, M. C., Drechsler, W., Morrissey, D., & King, J. (2001). Open and closed kinetic chain exercises in the early period after anterior cruciate ligament reconstruction: Improvements in level walking, stair ascent, and stair descent. *American Journal of Sports Medicine, 29*(2), 167-174.

Hooper, D. M., Morrissey, M. C., Drechsler, W. I., Clark, N. C., Coutts, F. J., & McAuliffe, T. B. (2002). Gait analysis 6 and 12 months after anterior cruciate ligament reconstruction surgery. *Clinical Orthopaedics and Related Research, 403*, 168-178.

Hunt, M. A., Birmingham, T. B., Giffin, J. R., & Jenkyn, T. R. (2006). Associations among knee adduction moment, frontal plane ground reaction force, and lever arm during walking in patients with knee osteoarthritis. *Journal of Biomechanics, 39*(12), 2213-2220.

Utah Health Status Survey, Utah Department of Health (2001). Interpreting SF-12: Assigning meaning to the PCS and MCS summary scores. Retrieved from (http://health.utah.gov/opha/publications/2001hss/sf12/SF12_Interpreting.pdf.

Janssen, K. W., Orchard, J. W., Driscoll, T. R., & van Mechelen, W. (2012). High incidence and costs for anterior cruciate ligament reconstructions performed in Australia from 2003-2004 to 2007-2008: time for an anterior cruciate ligament register by Scandinavian model? *Scand Journal of Medicine and Sciences in Sports, 22*(4), 495-501.

Jong, S. N. D., Caspel, D. R. V., Haeff, M. J. V., & Saris, D. B. (2007). Functional assessment and muscle strength before and after reconstruction of chronic anterior cruciate ligament lesions. *Arthroscopy : The Journal of Arthroscopic & Related Surgery : official publication of the Arthroscopy Association of North America and the International Arthroscopy Association, 23*(1), 21-28, 28.e21-23.

Jordan, K., Arden, N., Doherty, M., Bannwarth, B., Bijlsma, J., Dieppe, P., . . . Kaklamanis, P. (2003). EULAR Recommendations 2003: an evidence based approach to the management of knee osteoarthritis: Report of a Task Force of the Standing Committee for International Clinical Studies Including Therapeutic Trials (ESCISIT). *Annals of Rheumatic Diseases, 62*(12), 1145-1155.

Kannus, P. (1994). Isokinetic evaluation of muscular performance. *International Journal of Sports medicine, 15*(S 1), S11-S18.

Karimi, M., Fatoye, F., Mirbod, S. M., Omar, H., Nazem, K., Barzegar, M. R., & Hosseini, A. (2013). Gait analysis of anterior cruciate ligament reconstructed subjects with a combined tendon obtained from hamstring and peroneus longus. *Knee, 20*(6), 526-531.

Kartus, J., Magnusson, L., Stener, S., Brandsson, S., Eriksson, B. I., & Karlsson, J. (1999). Complications following arthroscopic anterior cruciate ligament reconstruction A 2–5-year follow-up of 604 patients with special emphasis on anterior knee pain. *Knee Surgery, Sports Traumatology, Arthroscopy, 7*(1), 2-8.

Kaur, M., Ribeiro, D. C., Theis, J.-C., Webster, K. E., & Sole, G. (2016). Movement patterns of the knee during gait following ACL reconstruction: A systematic review and meta-analysis. *Sports Medicine, 46*(12), 1-27.

Keays, S., Bullock-Saxton, J., & Keays, A. (2000). Strength and function before and after anterior cruciate ligament reconstruction. *Clinical Orthopaedics and Related Research, 373*, 174-183.

Keays, S., Bullock-Saxton, J. E., Keays, A. C., Newcombe, P. A., & Bullock, M. I. (2007). A 6-year follow-up of the effect of graft site on strength, stability, range of motion, function, and joint degeneration after anterior cruciate ligament reconstruction patellar tendon versus semitendinosus and gracilis tendon graft. *The American Journal of Sports Medicine, 35*(5), 729-739.

Keays, S., Newcombe, P. A., Bullock-Saxton, J. E., Bullock, M. I., & Keays, A. C. (2010). Factors involved in the development of osteoarthritis after anterior cruciate ligament surgery. *The American Journal of Sports Medicine, 38*(3), 455-463.

Khandha, A., Manal, K., Wellsandt, E., Capin, J., Snyder-Mackler, L., & Buchanan, T. S. (2016). Gait mechanics in those with/without medial compartment knee osteoarthritis 5 years after anterior cruciate ligament reconstruction. *Journal of Orthopaedic Research*. *35*(3), 625-633.

Kidd, M. O., Bond, C. H., & Bell, M. L. (2011). Patients' perspectives of patient-centredness as important in musculoskeletal physiotherapy interactions: a qualitative study. *Physiotherapy, 97*(2), 154-162.

Knoll, Z., Kiss, R. M., & Kocsis, L. (2004). Gait adaptation in ACL deficient patients before and after anterior cruciate ligament reconstruction surgery. *Journal of Electromyography and Kinesiology, 14*(3), 287-294.

Kocher, M. S., Steadman, J. R., Briggs, K., Zurakowski, D., Sterett, W. I., & Hawkins, R. J. (2002). Determinants of patient satisfaction with outcome after anterior cruciate ligament reconstruction. *Journal of Bone Joint Surgery American, 84*(9), 1560-1572.

Kowalk, D. L., Duncan, J. A., McCue, F. C., 3rd, & Vaughan, C. L. (1997). Anterior cruciate ligament reconstruction and joint dynamics during stair climbing. *Medicine & Science in Sports & Exercise, 29*(11), 1406-1413.

Kramer, J. F., Nusca, D., Fowler, P., & Webster-Bogaert, S. (1992). Test-retest reliability of the one-leg hop test following ACL reconstruction: LWW. 240-243.

Kuenze, C., Hertel, J., Weltman, A., Diduch, D. R., Saliba, S., & Hart, J. M. (2014). Jogging biomechanics after exercise in individuals with ACL-reconstructed knees. *Medicine Sciences in Sports Exercises, 46*(6), 1067-1076.

Kuenze, C. M., Hertel, J., Weltman, A., Diduch, D., Saliba, S. A., & Hart, J. M. (2015). Persistent neuromuscular and corticomotor quadriceps asymmetry after anterior cruciate ligament reconstruction. *Jounal of Athletic Trianing,* (3), 303-312.

Kutzner, I., Heinlein, B., Graichen, F., Bender, A., Rohlmann, A., Halder, A., Beier, A., Bergmann, G. (2010). Loading of the knee joint during activities of daily living measured in vivo in five subjects. *Journal of Biomechanics, 43*(11), 2164-2173.

Kvist, J., Ek, A., Sporrstedt, K., & Good, L. (2005). Fear of re-injury: a hindrance for returning to sports after anterior cruciate ligament reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy, 13*(5), 393-397.

Lafortune, M., Cavanagh, P., Sommer, H., & Kalenak, A. (1992). Three-dimensional kinematics of the human knee during walking. *Journal of Biomechanics, 25*(4), 347-357.

Lai, C. C., Ardern, C. L., Feller, J. A., & Webster, K. E. (2017). Eighty-three per cent of elite athletes return to preinjury sport after anterior cruciate ligament reconstruction: a systematic review with meta-analysis of return to sport rates, graft rupture rates and performance outcomes. *British Journal of Sports Medicine,* bjsports-2016-096836,

Lam, K. C., Thomas, S. S., Valier, A. R. S., McLeod, T. C. V., & Bay, C. (2015). Previous knee injury and health-related quality of life in collegiate athletes. *Journal of Athletic Training*. 52(6), 534-540

Laudner, K., Evans, D., Wong, R., Allen, A., Kirsch, T., Long, B., & Meister, K. (2015). Relationship between isokinetic knee strength and jump characteristics following anterior cruciate ligament reconstruction. *International Journal of Sports Physical Therapy, 10*(3), 272.

Lautamies, R., Harilainen, A., Kettunen, J., Sandelin, J., & Kujala, U. M. (2008). Isokinetic quadriceps and hamstring muscle strength and knee function 5 years after anterior cruciate ligament reconstruction: comparison between bone-patellar tendon-bone and hamstring tendon autografts. *Knee Surgery, Sports Traumatology, Arthroscopy, 16*(11), 1009-1016.

Leardini, A., Cappozzo, A., Catani, F., Toksvig-Larsen, S., Petitto, A., Sforza, V., Cassanelli, G., Giannini, S. (1999). Validation of a functional method for the estimation of hip joint centre location. *Journal of Biomechanics, 32*(1), 99-103.

Lee, D. Y., Karim, S. A., & Chang, H. C. (2008). Return to sports after anterior cruciate ligament reconstruction - a review of patients with minimum 5-year follow-up. *ANNALS Academy of Medicine Singapore, 37*(4), 273-278.

Lee, S.-H., Lee, J.-H., Ahn, S.-E., Park, M.-J., & Lee, D.-H. (2015). Correlation between quadriceps endurance and adduction moment in medial knee osteoarthritis. *PLOS ONE, 10*(11), e0141972.

Lepley, A. S., Ericksen, H. M., Sohn, D. H., & Pietrosimone, B. (2014). Contributions of neural excitability and voluntary activation to quadriceps muscle strength following anterior cruciate ligament reconstruction. *Knee, 21*(3), 736-742.

Lepley, L. K., & Palmieri-Smith, R. M. (2016). Pre-operative quadriceps activation is related to post-operative activation, not strength, in patients post-ACL reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy, 24*(1), 236-246.

Lewek, M., Rudolph, K., Axe, M., & Snyder-Mackler, L. (2002). The effect of insufficient quadriceps strength on gait after anterior cruciate ligament reconstruction. *Clinical Biomechanics (Bristol, Avon), 17*(1), 56-63.

Leys, T., Salmon, L., Waller, A., Linklater, J., & Pinczewski, L. (2012). Clinical results and risk factors for Reinjury 15 Years After anterior cruciate ligament reconstruction a prospective study of hamstring and patellar tendon grafts. *The American Journal of Sports Medicine, 40*(3), 595-605.

Li, H., Chen, C., & Chen, S. (2015). Posttraumatic knee osteoarthritis following anterior cruciate ligament injury: Potential biochemical mediators of degenerative alteration and specific biochemical markers (Review). *Biomedical reports, 3*(2), 147-151.

Li, R. T., Lorenz, S., Xu, Y., Harner, C. D., Fu, F. H., & Irrgang, J. J. (2011). Predictors of radiographic knee osteoarthritis after anterior cruciate ligament reconstruction. *American Journal of Sports Medicine, 39*(12), 2595-2603.

Lim, B. W., Kemp, G., Metcalf, B., Wrigley, T. V., Bennell, K. L., Crossley, K. M., & Hinman, R. S. (2009). The association of quadriceps strength with the knee adduction moment in medial knee osteoarthritis. *Arthritis care & Research, 61*(4), 451-458.

Logerstedt, D., Lynch, A., Axe, M. J., & Snyder-Mackler, L. (2013). Symmetry restoration and functional recovery before and after anterior cruciate ligament reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy,* 21(4), 859-868.

Lohmander, L. S., Englund, P. M., Dahl, L. L., & Roos, E. M. (2007). The long-term consequence of anterior cruciate ligament and meniscus injuries: osteoarthritis. *American Journal of Sports Medicine, 35*(10), 1756-1769.

Lynch, A. D., Logerstedt, D. S., Grindem, H., Eitzen, I., Hicks, G. E., Axe, M. J., . . . Snyder-Mackler, L. (2013). Consensus criteria for defining 'successful outcome' after ACL injury and reconstruction: A Delaware-Oslo ACL cohort investigation. *British Journal of Sports Medicine*. bjsports-2013.

Magnussen, R. A., Carey, J. L., & Spindler, K. P. (2011). Does autograft choice determine intermediate-term outcome of ACL reconstruction? *Knee Surgery Sports Traumatology Arthroscopy, 19*(3), 462-472.

Magnussen, R. A., Verlage, M., Flanigan, D. C., Kaeding, C. C., & Spindler, K. P. (2015). Patient-reported outcomes and their predictors at minimum 10 years after anterior cruciate ligament reconstruction: a systematic review of prospectively collected data. *Orthopaedic Journal of Sports Medicine, 3*(3), 2325967115573706.

Magyar, T. M., & Chase, M. A. (1996). Psychological strategies used by competitive gymnasts to overcome the fear of injury. *Technique, 16*, 1-5.

Malterud, K. (2001). Qualitative research: standards, challenges, and guidelines. *The lancet, 358*(9280), 483-488.

Manal, K., Gardinier, E., Snyder-Mackler, L., & Buchanan, T. (2013). An alternate predictor of peak medial compartment loading: the product of the peak knee extensor and abductor moments *American Society of Biomechanics*.

Mattacola, C. G., Perrin, D. H., Gansneder, B. M., Gieck, J. H., Saliba, E. N., & McCue, I. F. C. (2002). Strength, functional outcome, and postural stability after anterior cruciate ligament reconstruction. *Journal of Athletic Training, 37*(3), 262-268.

McFadyen, B. J., & Winter, D. A. (1988). An integrated biomechanical analysis of normal stair ascent and descent. *Journal of Biomechanics, 21*(9), 733-744.

Messier, S. P., Gutekunst, D. J., Davis, C., & DeVita, P. (2005). Weight loss reduces knee-joint loads in overweight and obese older adults with knee osteoarthritis. *Arthritis & Rheumatology, 52*(7), 2026-2032.

Meunier, A., Odensten, M., & Good, L. (2007). Long-term results after primary repair or non-surgical treatment of anterior cruciate ligament rupture: A randomized study with a 15-year follow-up. *Scandivian Journal of Medicine Sciencea and Sports, 17*(3), 230-237.

Mihelic, R., Jurdana, H., Jotanovic, Z., Madjarevic, T., & Tudor, A. (2011). Long-term results of anterior cruciate ligament reconstruction: a comparison with non-operative treatment with a follow-up of 17–20 years. *International Orthopedics, 35*(7), 1093-1097.

Miyazaki, T., Wada, M., Kawahara, H., Sato, M., Baba, H., & Shimada, S. (2002). Dynamic load at baseline can predict radiographic disease progression in medial compartment knee osteoarthritis. *Annals of Rheumatic Diseases, 61*(7), 617-622.

Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2009). Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *Annals of Internal Medicine, 151*(4), 264-269.

Moisio, K. C., Sumner, D. R., Shott, S., & Hurwitz, D. E. (2003). Normalization of joint moments during gait: a comparison of two techniques. *Journal of Biomechanics, 36*(4), 599-603.

Moisio, K. C., Sumner, D. R., Shott, S., & Hurwitz, D. E. (2003). Normalization of joint moments during gait: a comparison of two techniques. *Journal of Biomechanics*, 36(4), 599-603.

Möller, E., Weidenhielm, L., & Werner, S. (2009). Outcome and knee-related quality of life after anterior cruciate ligament reconstruction: a long-term follow-up. *Knee Surgery, Sports Traumatology, Arthroscopy, 17*(7), 786-794.

Morgan, D. L. (1998). Practical strategies for combining qualitative and quantitative methods: Applications to health research. *Qualitative Health Research, 8*(3), 362-376.

Muller, B., Yabroudi, M. A., Lynch, A., Lai, C.-L., Van Dijk, C. N., Fu, F. H., & Irrgang, J. J. (2016). Defining thresholds for the patient acceptable symptom state for the IKDC subjective knee form and KOOS for patients who underwent ACL reconstruction. *The American Journal of Sports Medicine*, 44(11), 2820-2826.

Mundermann, A., Asay, J. L., Mundermann, L., & Andriacchi, T. P. (2008). Implications of increased medio-lateral trunk sway for ambulatory mechanics. *Journal of Biomechanics, 41*(1), 165-170.

Mündermann, A., Dyrby, C. O., & Andriacchi, T. P. (2005). Secondary gait changes in patients with medial compartment knee osteoarthritis: increased load at the ankle, knee, and hip during walking. *Arthritis & Rheumatism, 52*(9), 2835-2844.

Mündermann, A., Dyrby, C. O., Hurwitz, D. E., Sharma, L., & Andriacchi, T. P. (2004). Potential strategies to reduce medial compartment loading in patients with knee osteoarthritis of varying severity: reduced walking speed. *Arthritis & Rheumatism, 50*(4), 1172-1178.

Munro, B. H. (2005). *Statistical methods for health care research* (Vol. 1): Lippincott Williams & Wilkins.

Myer, G. D., Chu, D. A., Brent, J. L., & Hewett, T. E. (2008). Trunk and hip control neuromuscular training for the prevention of knee joint injury. *Clinical Sports Medicine, 27*(3), 425-448.

Myers, B. A., Jenkins, W. L., Killian, C., & Rundquist, P. (2014). Normative data for hop tests in high school and collegiate basketball and soccer players. *International Journal of Sports Physical Therapy, 9*(5), 596.

Neeter, C., Gustavsson, A., Thomeé, P., Augustsson, J., Thomeé, R., & Karlsson, J. (2006). Development of a strength test battery for evaluating leg muscle power after anterior cruciate ligament injury and reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy, 14*(6), 571-580.

NZ Orthopaedic Surgeons Association. (2016). New Zealand ACL registry Annual report 2016. Retrieved from https://nzoa.org.nz//system/files/New%20Zealand%20ACL%20Registry%20Annual%20Report%202016.

Nigg, B. M., MacIntosh, B. R., & Mester, J. (2000). *Biomechanics and biology of movement*. IL, USA: Human Kinetics.

Noehren, B., Wilson, H., Miller, C., & Lattermann, C. (2013). Long-term gait deviations in anterior cruciate ligament-reconstructed females. *Medicine Science Sports and Exercise, 45*(7), 1340-1347.

Noyes, F. R., Barber, S. D., & Mangine, R. E. (1991). Abnormal lower limb symmetry determined by function hop tests after anterior cruciate ligament rupture. *The American Journal of Sports Medicine, 19*(5), 513-518.

Nyland, J., Klein, S., & Caborn, D. N. (2010). Lower extremity compensatory neuromuscular and biomechanical adaptations 2 to 11 years after anterior cruciate ligament reconstruction. *Arthroscopy : The Journal of Arthroscopic & Related Surgery : official publication of the Arthroscopy Association of North America and the International Arthroscopy Association, 26*(9), 1212-1225.

Øiestad, B., Juhl, C., Eitzen, I., & Thorlund, J. (2015). Knee extensor muscle weakness is a risk factor for development of knee osteoarthritis. A systematic review and meta-analysis. *Osteoarthritis and Cartilage, 23*(2), 171-177.

Øiestad, B. E., Engebretsen, L., Storheim, K., & Risberg, M. A. (2009). Knee osteoarthritis after anterior cruciate ligament injury a systematic review. *The American Journal of Sports Medicine, 37*(7), 1434-1443.

Oiestad, B. E., Holm, I., Gunderson, R., Myklebust, G., & Risberg, M. A. (2010). Quadriceps muscle weakness after anterior cruciate ligament reconstruction: a risk factor for knee osteoarthritis? *Arthritis Care & Research, 62*(12), 1706-1714.

Orishimo, K. F., Kremenic, I. J., Mullaney, M. J., McHugh, M. P., & Nicholas, S. J. (2010). Adaptations in single-leg hop biomechanics following anterior cruciate ligament reconstruction. *Knee Surgery Sports Traumatology Arthroscopy, 18*(11), 1587-1593.

Otzel, D. M., Chow, J. W., & Tillman, M. D. (2015). Long-term deficits in quadriceps strength and activation following anterior cruciate ligament reconstruction. *Physical Therapy in SportS, 16*(1), 22-28.

Palmieri-Smith, R. M., & Lepley, L. K. (2015). Quadriceps strength asymmetry after anterior cruciate ligament reconstruction alters knee joint biomechanics and functional performance at time of return to activity. *American Journal of Sports Medicine, 43*(7), 1662-1669.

Palmieri-Smith, R. M., Thomas, A. C., Karvonen-Gutierrez, C., & Sowers, M. F. (2010). Isometric quadriceps strength in women with mild, moderate, and severe knee osteoarthritis. *American Journal of Physical Medicine & Rehabilitation/Association of Academic Physiatrists, 89*(7), 541.

Patel, R. R., Hurwitz, D. E., Bush-Joseph, C. A., Bach, B. R., Jr., & Andriacchi, T. P. (2003). Comparison of clinical and dynamic knee function in patients with anterior cruciate ligament deficiency. *American Journal of Sports Medicine, 31*(1), 68-74.

Pataky, T. C. (2012). One-dimensional statistical parametric mapping in Python. *Computer Methods in Biomechanics and Biomedical Engineering,* 15(3), 295-301.

Paterno, M. V., Ford, K. R., Myer, G. D., Heyl, R., & Hewett, T. E. (2007). Limb asymmetries in landing and jumping 2 years following anterior cruciate ligament reconstruction. *Clinical Journal of Sport Medicine, 17*(4), 258-262.

Paterno, M. V., Rauh, M. J., Schmitt, L. C., Ford, K. R., & Hewett, T. E. (2012). Incidence of contralateral and ipsilateral anterior cruciate ligament (ACL) injury after primary ACL reconstruction and return to sport. *Clininical Journal of Sport Medicine, 22*(2), 116-121.

Paterno, M. V., Schmitt, L. C., Ford, K. R., Rauh, M. J., Myer, G. D., Huang, B., & Hewett, T. E. (2010). Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. *American Journal of Sports Medicine*, *38*(10), 1968-1978.

Patterson, M. R., Delahunt, E., & Caulfield, B. (2014). Peak knee adduction moment during gait in anterior cruciate ligament reconstructed females. *Clinical Biomechanics, 29*(2), 138-142.

Paterson, K., Bennell, K., Wrigley, T., Metcalf, B., Kasza, J., & Hinman, R. (2017). Effects of footwear on the knee adduction moment in medial knee osteoarthritis: classification criteria for flat flexible vs stable supportive shoes. *Osteoarthritis and Cartilage*, 25(2), 234-241.

Petersen, W., Taheri, P., Forkel, P., & Zantop, T. (2014). Return to play following ACL reconstruction: a systematic review about strength deficits. *Archives of Orthopaedic and Trauma Surgery, 134*(10), 1417-1428.

Petschnig, R., Baron, R., & Albrecht, M. (1998). The relationship between isokinetic quadriceps strength test and hop tests for distance and one-legged vertical jump test following anterior cruciate ligament reconstruction. *Journal of Orthopaedic & Sports Physical Therapy, 28*(1), 23-31.

Pietrosimone, B., Loeser, R. F., Blackburn, J. T., Padua, D. A., Harkey, M. S., Stanley, L. E., . . . Jordan, J. M. (2017). Biochemical markers of cartilage metabolism are associated with walking biomechanics 6-months following anterior cruciate ligament reconstruction. *Journal of Orthopaedic Research*. 35(10), 2288-2297.

Pietrosimone, B., McLeod, M. M., & Lepley, A. S. (2012). A theoretical framework for understanding neuromuscular response to lower extremity joint injury. *Sports Health, 4*(1), 31-35.

Pohl, M. B., Lloyd, C., & Ferber, R. (2010). Can the reliability of three-dimensional running kinematics be improved using functional joint methodology? *Gait Posture, 32*(4), 559-563.

Pozzi, F., Di Stasi, S., Zeni, J. A., & Barrios, J. A. (2017). Single-limb drop landing biomechanics in active individuals with and without a history of anterior cruciate ligament reconstruction: A total support analysis. *Clinical Biomechanics, (43)*, 28-33.

Quality of life in Sothern Australia, March 2005, Retrieved from https://health.adelaide.edu.au/pros/docs/reports/general/qol_quality_of_life_sf_12.

Quinn, F., Johnston, M., Dixon, D., Johnston, D. W., Pollard, B., & Rowley, D. I. (2012). Testing the integration of ICF and behavioral models of disability in orthopedic patients: Replication and extension. *Rehabilitation Psychology, 57*(2), 167.

Radzimski, A. O., Mündermann, A., & Sole, G. (2012). Effect of footwear on the external knee adduction moment—a systematic review. *Knee, 19*(3), 163-175.

Rayan, F., Nanjayan, S. K., Quah, C., Ramoutar, D., Konan, S., & Haddad, F. S. (2015). Review of evolution of tunnel position in anterior cruciate ligament reconstruction. *World Journal of Orthopedics, 6*(2), 252.

Reid, A., Birmingham, T. B., Stratford, P. W., Alcock, G. K., & Giffin, J. R. (2007). Hop testing provides a reliable and valid outcome measure during rehabilitation after anterior cruciate ligament reconstruction. *Physical Therapy, 87*(3), 337-349.

Reiman, M. P., & Manske, R. C. (2009). Functional testing in human performance. Champaign (IL):Human kinetics.

Robbins, S. M., & Maly, M. R. (2009). The effect of gait speed on the knee adduction moment depends on waveform summary measures. *Gait Posture, 30*(4), 543-546.

Roewer, B. D., Di Stasi, S. L., & Snyder-Mackler, L. (2011). Quadriceps strength and weight acceptance strategies continue to improve two years after anterior cruciate ligament reconstruction. *Journal of Biomechanics, 44*(10), 1948-1953.

Ronsky, J., & Yeadon, M. (1993). Application of the joint coordinate system to three-dimensional joint attitude and movement representation: a standardization proposal. 115(4A), 344-349.

Roos, E. M., & Lohmander, L. S. (2003). The Knee injury and Osteoarthritis Outcome Score (KOOS): from joint injury to osteoarthritis. *Health and Quality of Life Outcomes, 1*(1), 64.

Roos, E. M., Roos, H. P., Lohmander, L. S., Ekdahl, C., & Beynnon, B. D. (1998). Knee Injury and Osteoarthritis Outcome Score (KOOS)—development of a self-administered outcome measure. *Journal of Orthopaedic & Sports Physical Therapy, 28*(2), 88-96.

Roos, H., Adalberth, T., Dahlberg, L., & Lohmander, L. S. (1995). Osteoarthritis of the knee after injury to the anterior cruciate ligament or meniscus: the influence of time and age. *Osteoarthritis Cartilage, 3*(4), 261-267.

Roos, P. J., Neu, C. P., Hull, M. L., & Howell, S. M. (2005). A new tibial coordinate system improves the precision of anterior-posterior knee laxity measurements: a cadaveric study using Roentgen stereophotogrammetric analysis. *Journal of Orthopaedic Research, 23*(2), 327-333.

Ross, C. A., Clifford, A., & Louw, Q. A. (2017). Factors informing fear of reinjury after anterior cruciate ligament reconstruction. *Physiotherapy Theory and Practice, 33*(2), 103-114.

Sakane, M., Fox, R. J., Glen, S. L. Y. W., Livesay, A., Li, G., & Fu, F. H. (1997). In situ forces in the anterior cruciate ligament and its bundles in response to anterior tibial loads. *Journal of Orthopaedic Research, 15*(2), 285-293.

Salaffi, F., Carotti, M., Stancati, A., & Grassi, W. (2005). Health-related quality of life in older adults with symptomatic hip and knee osteoarthritis: a comparison with matched healthy controls. *Aging Clinical and Experimental research, 17*(4), 255-263.

Salavati, M., Akhbari, B., Mohammadi, F., Mazaheri, M., & Khorrami, M. (2011). Knee injury and Osteoarthritis Outcome Score (KOOS); reliability and validity in competitive athletes after anterior cruciate ligament reconstruction. *Osteoarthritis and Cartilage, 19*(4), 406-410.

Salmon, L., Russell, V., Musgrove, T., Pinczewski, L., & Refshauge, K. (2005). Incidence and risk factors for graft rupture and contralateral rupture after anterior cruciate ligament reconstruction. *Arthroscopy : The Journal of Arthroscopic & Related Surgery : official publication of the Arthroscopy Association of North America and the International Arthroscopy Association, 21*(8), 948-957.

Salmon, L. J., Russell, V. J., Refshauge, K., Kader, D., Connolly, C., Linklater, J., & Pinczewski, L. A. (2006). Long-term outcome of endoscopic anterior cruciate ligament reconstruction with patellar tendon autograft minimum 13-year review. *The American Journal of Sports Medicine, 34*(5), 721-732.

Sanders, T. L., Kremers, H. M., Bryan, A. J., Larson, D. R., Dahm, D. L., Levy, B. A., Stuart, MJ., Krych, A. J. (2016). Incidence of anterior cruciate ligament tears and reconstruction a 21-year population-based study. *The American Journal of Sports Medicine, 44*(6), 1502-1507.

Sato, K., Maeda, A., Takano, Y., Matsuse, H., Ida, H., & Shiba, N. (2013). Relationship between static anterior laxity using the KT-1000 and dynamic tibial rotation during motion in patients with anatomical anterior cruciate ligament reconstruction. *Kurume Medical Journal, 60*(1), 1-6.

Saxby, D. J., Bryant, A. L., Modenese, L., Gerus, P., Killen, B., Konrath, J., Cicuttini, F. M. (2016). Tibiofemoral contact forces in the anterior cruciate ligament-reconstructed knee. *Medicine Science and Sports Exercise,* 48(11), 2195-2206.

Scanlan, S. F., Blazek, K., Chaudhari, A. M. W., Safran, M. R., & Andriacchi, T. P. (2009). Graft orientation influences the knee flexion moment during walking in patients with anterior cruciate ligament reconstruction. *American Journal of Sports Medicine, 37*(11), 2173-2178.

Scanlan, S. F., Chaudhari, A. M., Dyrby, C. O., & Andriacchi, T. P. (2010). Differences in tibial rotation during walking in ACL reconstructed and healthy contralateral knees. *Journal of Biomechanics, 43*(9), 1817-1822.

Schipplein, O., & Andriacchi, T. (1991). Interaction between active and passive knee stabilizers during level walking. *Journal of Orthopaedic Research, 9*(1), 113-119.

Schmalz, T., Blumentritt, S., Wagner, R., & Gokeler, A. (1998). Gait analysis of patients within one year after ACL reconstruction. *Physikalische Medizin Rehabilitationsmedizin Kurortmedizin, 8*(1), 1-8.

Schmalz, T., Blumentritt, S., Wagner, R., & Junge, R. (1998). Evaluation with biomechanical gait analysis of various treatment methods after rupture of the anterior cruciate ligament. [German]. [Biomechanisch-ganganalytische Bewertung verschiedener Behandlungsmethoden nach Ruptur des vorderen Kreuzbandes.]. *Sportverletz Sportschaden, 12*(4), 131-137.

Schmitt, L. C., Paterno, M. V., Ford, K. R., Myer, G. D., & Hewett, T. E. (2015). Strength asymmetry and landing mechanics at return to sport after anterior cruciate ligament reconstruction. *Medicine and Science in Sports and Exercise, 47*(7), 1426-1434.

Schmitt, L. C., Paterno, M. V., & Hewett, T. E. (2012). The impact of quadriceps femoris strength asymmetry on functional performance at return to sport following anterior cruciate ligament reconstruction. *Journal of Orthopaedic & Sports Physical Therapy, 42*(9), 750-759.

Schmitz, A., & Noehren, B. (2014). What predicts the first peak of the knee adduction moment? *Knee, 21*(6), 1077-1083.

Schroeder, M. J., Krishnan, C., & Dhaher, Y. Y. (2015). The influence of task complexity on knee joint kinetics following ACL reconstruction. *Clinical Biomechanics, 30*(8), 852-859.

Scott, S. M., Perry, M. A., & Sole, G. (2017). “Not always a straight path”: patients’ perspectives following anterior cruciate ligament rupture and reconstruction. *Disability and Rehabilitation*, 1-7.

Semay, B., Rambaud, A., Philippot, R., & Edouard, P. (2016). Evolution of the anteroposterior laxity by GnRB at 6, 9 and 12 months post-surgical anterior cruciate ligament reconstruction. *Annals of Physical and Rehabilitation Medicine, 59,* e19.

Senorski, E. H., Sundemo, D., Murawski, C. D., Alentorn-Geli, E., Musahl, V., Fu, F. (2017) Samuelsson, K. No differences in subjective knee function between surgical techniques of anterior cruciate ligament reconstruction at 2-year follow-up: a cohort study from the Swedish National Knee Ligament Register. *Knee Surgery, Sports Traumatology, Arthroscopy*, 1-10.

Sernert, N., Kartus, J., Köhler, K., Ejerhed, L., Brandsson, S., & Karlsson, J. (2002). Comparison of functional outcome after anterior cruciate ligament reconstruction resulting in low, normal and increased laxity. *Scandivian Journal of Medicine and Science in Sports, 12*(1), 47-53.

Setton, L. A., Elliott, D. M., & Mow, V. C. (1999). Altered mechanics of cartilage with osteoarthritis: human osteoarthritis and an experimental model of joint degeneration. *Osteoarthritis and Cartilage, 7*(1), 2-14.

Sharma, L., Hurwitz, D. E., Eugene, J. A. T., Sum, J. A., Lenz, M. E., Dunlop, D. D., . . . Andriacchi, T. P. (1998). Knee adduction moment, serum hyaluronan level, and disease severity in medial tibiofemoral osteoarthritis. *Age, 6*(9), 15.

Shelbourne, K. D., Gray, T., & Haro, M. (2009). Incidence of subsequent injury to either knee within 5 years after anterior cruciate ligament reconstruction with patellar tendon autograft. *The American Journal of Sports Medicine, 37*(2), 246-251.

Shelbourne, K. D., Klootwyk, T. E., Wilckens, J. H., & De Carlo, M. S. (1995). Ligament stability two to six years after anterior cruciate ligament reconstruction with autogenous patellar tendon graft and participation in accelerated rehabilitation program. *The American Journal of Sports Medicine*, *23*(5), 575-579.

Shelburne, K. B., Torry, M. R., & Pandy, M. G. (2006). Contributions of muscles, ligaments, and the ground-reaction force to tibiofemoral joint loading during normal gait. *Journal of Orthopaedic Research, 24*(10), 1983-1990.

Sherman, O. H., & Banffy, M. B. (2004). Anterior cruciate ligament reconstruction: which graft is best? *Arthroscopy: The Journal of Arthroscopic & Related Surgery, 20*(9), 974-980.

Simic, M., Hinman, R. S., Wrigley, T. V., Bennell, K. L., & Hunt, M. A. (2011). Gait modification strategies for altering medial knee joint load: a systematic review. *Arthritis care & Research*, *63*(3), 405-426.

Simic, M., Hunt, M. A., Bennell, K. L., Hinman, R. S., & Wrigley, T. V. (2012). Trunk lean gait modification and knee joint load in people with medial knee osteoarthritis: the effect of varying trunk lean angles. *Arthritis care & Research, 64*(10), 1545-1553.

Slemenda, C., Brandt, K. D., Heilman, D. K., Mazzuca, S., Braunstein, E. M., Katz, B. P., & Wolinsky, F. D. (1997). Quadriceps weakness and osteoarthritis of the knee. *Annals of internal medicine*, *127*(2), 97-104.

Smith, F., Rosenlund, E., Aune, A., MacLean, J., & Hillis, S. (2004). Subjective functional assessments and the return to competitive sport after anterior cruciate ligament reconstruction. *British Journal of Sports Medicine, 38*(3), 279-284.

Sole, G., Hamrén, J., Milosavljevic, S., Nicholson, H., & Sullivan, S. J. (2007). Test-retest reliability of isokinetic knee extension and flexion. *Archives of Physical Medicine and Rehabilitation, 88*(5), 626-631.

Sole, G., Tengman, E., Grip, H., & Häger, C. K. (2016). Knee kinematics during stair descent 20years following anterior cruciate ligament rupture with and without reconstruction. *Clinical Biomechanics, 32*, 180-186.

Sole, G., Pataky, T., Tengman, E., & Häger, C. (2017). Analysis of three-dimensional knee kinematics during stair descent two decades post-ACL rupture–Data revisited using statistical parametric mapping. *Journal of Electromyography and Kinesiology, 32*, 44-50.

Sonesson, S., Kvist, J., Ardern, C., Österberg, A., & Silbernagel, K. G. (2017). Psychological factors are important to return to pre-injury sport activity after anterior cruciate ligament reconstruction: expect and motivate to satisfy. *Knee Surgery, Sports Traumatology, Arthroscopy,* 25(5), 1375-1384.

Sorsa, M. A., Kiikkala, I., & Åstedt-Kurki, P. (2015). Bracketing as a skill in conducting unstructured qualitative interviews. *Nurse researcher, 22*(4), 8-12.

Sosdian, L., Dobson, F., Wrigley, T., Paterson, K., Bennell, K., Dowsey, M., Choong, P., Allison, K Hinman, R. (2014). Longitudinal changes in knee kinematics and moments following knee arthroplasty: A systematic review. *Knee, 21*(6), 994-1008.

Spindler, K. P., Kuhn, J. E., Freedman, K. B., Matthews, C. E., Dittus, R. S., & Harrell, F. E. (2004). Anterior cruciate ligament reconstruction autograft choice: bone-tendon-bone versus hamstring does it really matter? A systematic review. *The American Journal of Sports Medicine, 32*(8), 1986-1995.

Stebbins, J., Trinler, U. K., Baker, R., Brunner, R., Wren, T., & Theologis, T. (2015). Recommendations for reporting gait studies. *Gait Posture, 41*(2), 339-340.

Strutzenberger, G., Richter, A., Schneider, M., Mündermann, A., & Schwameder, H. (2011). Effects of obesity on the biomechanics of stair-walking in children. *Gait Posture, 34*(1), 119-125.

Stucki, G., Cieza, A., & Melvin, J. (2007). The international classification of functioning, disability and health: A unifying model for the conceptual description of the rehabilitation strategy. *Journal of Rehabilitation Medicine, 39*(4), 279-285.

Swärd, P., Kostogiannis, I., & Roos, H. (2010). Risk factors for a contralateral anterior cruciate ligament injury. *Knee Surgery, Sports Traumatology, Arthroscopy, 18*(3), 277-291.

Sweet, L. (2002). Telephone interviewing: is it compatible with interpretive phenomenological research? *Contemporary Nurse, 12*(1), 58-63.

Tagesson, S., Oberg, B., & Kvist, J. (2015). Static and dynamic tibial translation before, 5 weeks after, and 5 years after anterior cruciate ligament reconstruction. *Knee Surgery Sports Traumatology Arthroscopy, 23*(12), 3691-3697.

Tanner, S. M., Dainty, K. N., Marx, R. G., & Kirkley, A. (2007). Knee-Specific Quality-of-Life Instruments Which Ones Measure Symptoms and Disabilities Most Important to Patients? *The American Journal of Sports Medicine, 35*(9), 1450-1458.

Tashman, S., Collon, D., Anderson, K., Kolowich, P., & Anderst, W. (2004). Abnormal rotational knee motion during running after anterior cruciate ligament reconstruction. *American Journal of Sports Medicine, 32*(4), 975-983.

Teddlie, C., & Tashakkori, A. (2009). Foundations of mixed methods research: Integrating quantitative and qualitative approaches in the social and behavioral sciences: *Sage.*

Tegner, Y., & Lysholm, J. (1985). Rating systems in the evaluation of knee ligament injuries. *Clinical Orthopaedics and Related Research, (198),* 42-49.

Tengman, E. (2014). Long-term consequences of anterior cruciate ligament injury: knee function, physical activity level, physical capacity and movement pattern. (Doctoral dissertation, Umeå University).

Tengman, E., Brax Olofsson, L., Nilsson, K. G., Tegner, Y., Lundgren, L., & Häger, C. (2014). Anterior cruciate ligament injury after more than 20 years: I. Physical activity level and knee function. *Scandivian Journal of Medicine and Science in Sports, 24*(6), e491-500.

Tengman, E., Brax Olofsson, L., Stensdotter, A.-K., Nilsson, K. G., & Häger, C. (2014). Anterior cruciate ligament injury after more than 20 years. II. Concentric and eccentric knee muscle strength. *Scandivian Journal of Medicine and Science in Sports, 24*(6), e501-509.

Tengman, E., Grip, H., & Hager, C. (2013). One-leg hop-kinematic analysis ~20 years after anterior cruciate ligament injury. *Gait and posture, (38),* S25-S26.

Thing, L. F. (2006). “Voices of the broken body.” The resumption of non-professional female players' sports careers after anterior cruciate ligament injury. The female player's dilemma: is she willing to run the risk? *Scandivian Journal of Medicine and Science in Sports, 16*(5), 364-375.

Thomas, D. R. (2006). A general inductive approach for analyzing qualitative evaluation data. *American Journal of Evaluation, 27*(2), 237-246.

Thomeé, R., Neeter, C., Gustavsson, A., Thomeé, P., Augustsson, J., Eriksson, B., & Karlsson, J. (2012). Variability in leg muscle power and hop performance after anterior cruciate ligament reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy, 20*(6), 1143-1151.

Timoney, J. M., Inman, W. S., Quesada, P. M., Sharkey, P. F., Barrack, R. L., Skinner, H. B., & Alexander, A. H. (1993). Return of normal gait patterns after anterior cruciate ligament reconstruction. *American Journal of Sports Medicine, 21*(6), 887-889.

Tong, A., Sainsbury, P., & Craig, J. (2007). Consolidated criteria for reporting qualitative research (COREQ): a 32-item checklist for interviews and focus groups. *International Journal for Quality in Health Care, 19*(6), 349-357.

Tourville, T. W., Jarrell, K. M., Naud, S., Slauterbeck, J. R., Johnson, R. J., & Beynnon, B. D. (2014). Relationship between isokinetic strength and tibiofemoral joint space width changes after anterior cruciate ligament reconstruction. *The American Journal of Sports Medicine, 42*(2), 302-311.

Trigsted, S. M., Post, E. G., & Bell, D. R. (2017). Landing mechanics during single hop for distance in females following anterior cruciate ligament reconstruction compared to healthy controls. *Knee Surgery, Sports Traumatology, Arthroscopy*, 25(5), 1395-1402.

Trinler, U. K., Baty, F., Mundermann, A., Fenner, V., Behrend, H., Jost, B., & Wegener, R. (2016). Stair dimension affects knee kinematics and kinetics in patients with good outcome after TKA similarly as in healthy subjects. *Journal of Orthopaedic Research : official publication of the Orthopaedic Research Society, 34*(10), 1753-1761.

Turner, A. P., Barlow, J. H., & Heathcote-Elliott, C. (2000). Long term health impact of playing professional football in the United Kingdom. *British Journal of Sports Medicine, 34*(5), 332-336.

Undheim, M. B., Cosgrave, C., King, E., Strike, S., Marshall, B., Falvey, É., & Franklyn-Miller, A. (2015). Isokinetic muscle strength and readiness to return to sport following anterior cruciate ligament reconstruction: is there an association? A systematic review and a protocol recommendation. *British Journal of Sports Medicine*, 49(20), 1305-1310.

Urbach, D., Nebelung, W., Becker, R., & Awiszus, F. (2001). Effects of reconstruction of the anterior cruciate ligament on voluntary activation of quadriceps femoris a prospective twitch interpolation study. *Journal of Bone & Joint Surgery - British Volume, 83*(8), 1104-1110.

Urbach, D., Nebelung, W., Röpke, M., Becker, R., & Awiszus, F. (2000). [Bilateral dysfunction of the quadriceps muscle after unilateral cruciate ligament rupture with concomitant injury central activation deficit]. *Unfallchirurg, 103*(11), 949-955.

Urbaniak, G., & Plous, S. (2013). Research Randomizer (Version 4.0)[Computer software]. Retrieved on June 22, 2013.

Valderrabano, V., & Steiger, C. (2010). Treatment and prevention of osteoarthritis through exercise and sports. *Journal of Aging Research, 2011*;2011:374653.

Valeriani, M., Restuccia, D., Lazzaro, V. D., Franceschi, F., Fabbriciani, C., & Tonali, P. (1996). Central nervous system modifications in patients with lesion of the anterior cruciate ligament of the knee. *Brain, 119*(5), 1751-1762.

Van den Akker-Scheek, I., Stevens, M., Groothoff, J. W., Bulstra, S. K., & Zijlstra, W. (2007). Preoperative or postoperative self-efficacy: which is a better predictor of outcome after total hip or knee arthroplasty? *Patient Education and Counseling*, 66(1), 92-99.

Van Griensven, H., Moore, A. P., & Hall, V. (2014). Mixed methods research–The best of both worlds? *Manual Therapy, 19*(5), 367-371.

Van Thiel, G., & Bach, B. (2010). Arthrometric evaluation of the failed ACL: Normal ACL, Injured ACL, Reconstructed ACL, and the Failed ACL. *ACL Surgery: How to Get it Right the First Time and What to do if it Fails*, 191-202.

Van Tulder, M., Furlan, A., Bombardier, C., Bouter, L., & Group, E. B. o. t. C. C. B. R. (2003). Updated method guidelines for systematic reviews in the Cochrane Collaboration Back Review Group. *Spine, 28*(12), 1290-1299.

Varma, R. K., Duffell, L. D., Nathwani, D., & McGregor, A. H. (2014). Knee moments of anterior cruciate ligament reconstructed and control participants during normal and inclined walking. *BMJ Open, 4*(6), e004753.

Von Aesch, A. V., Perry, M., & Sole, G. (2016). Physiotherapists' experiences of the management of anterior cruciate ligament injuries. *Physical Therapy in Sport, 19*, 14-22.

Von Elm, E., Altman, D. G., Egger, M., Pocock, S. J., Gøtzsche, P. C., Vandenbroucke, J. P., & Initiative, S. (2014). The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) Statement: guidelines for reporting observational studies. *International Journal of Surgery, 12*(12), 1495-1499.

Von Porat, A., Roos, E., & Roos, H. (2004). High prevalence of osteoarthritis 14 years after an anterior cruciate ligament tear in male soccer players: a study of radiographic and patient relevant outcomes. *Annals of Rheumatic Diseases, 63*(3), 269-273.

Walter, J. P., D'Lima, D. D., Colwell, C. W., & Fregly, B. J. (2010). Decreased knee adduction moment does not guarantee decreased medial contact force during gait. *Journal of Orthopaedic Research, 28*(10), 1348-1354.

Wang, H., Fleischli, J. E., & Nigel Zheng, N. (2012). Effect of lower limb dominance on knee joint kinematics after anterior cruciate ligament reconstruction. *Clinical Biomechanics, 27*(2), 170-175.

Wang, H. S., Fleischli, J. E., & Zheng, N. Q. (2013). Transtibial versus anteromedial portal technique in single-bundle anterior cruciate ligament reconstruction outcomes of knee joint kinematics during walking. *American Journal of Sports Medicine, 41*(8), 1847-1856.

Wang, W. M., Zhao, D. W., Cui, D. P., Li, R. X., Liu, Y. P., & Yang, S. (2009). Gait analysis associated with anterior cruciate ligament reconstruction. [Chinese]. *Zhonghua Yi Xue Za Zhi, 89*(29), 2025-2029.

Ware Jr, J. E., Kosinski, M., & Keller, S. D. (1996). A 12-Item Short-Form Health Survey: construction of scales and preliminary tests of reliability and validity. *Medical care, 34*(3), 220-233.

Webster, K. E., & Feller, J. A. (2011). Alterations in joint kinematics during walking following hamstring and patellar tendon anterior cruciate ligament reconstruction surgery. *Clinical Biomechanics (Bristol, Avon), 26*(2), 175-180.

Webster, K. E., & Feller, J. A. (2012a). The knee adduction moment in hamstring and patellar tendon anterior cruciate ligament reconstructed knees. *Knee Surgery Sports Traumatology Arthroscopy, 20*(11), 2214-2219.

Webster, K. E., & Feller, J. A. (2012b). Tibial rotation in anterior cruciate ligament reconstructed knees during single limb hop and drop landings. *Clinical Biomechanics, 27*(5), 475-479.

Webster, K. E., & Feller, J. A. (2014). Use of the short form health surveys as an outcome measure for anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatology Arthroscopy, 22*(5), 1142-1148.

Webster, K. E., Feller, J. A., & Wittwer, J. E. (2012). Longitudinal changes in knee joint biomechanics during level walking following anterior cruciate ligament reconstruction surgery. *Gait Posture, 36*(2), 167-171.

Webster, K. E., Gonzalez-Adrio, R., & Feller, J. A. (2004). Dynamic joint loading following hamstring and patellar tendon anterior cruciate ligament reconstruction. *Knee Surgery Sports Traumatology Arthroscopy, 12*(1), 15-21.

Webster, K. E., McClelland, J. A., Palazzolo, S. E., Santamaria, L. J., & Feller, J. A. (2012). Gender differences in the knee adduction moment after anterior cruciate ligament reconstruction surgery. *British Journal of Sports Medicine, 46*(5), 355-359.

Webster, K. E., Wittwer, J. E., O'Brien, J., & Feller, J. A. (2005). Gait patterns after anterior cruciate ligament reconstruction are related to graft type. *American Journal of Sports Medicine, 33*(2), 247-254.

Weir, J. P. (2005). Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. *Journal of Strength and Conditioning Research, 19*(1), 231-240.

Wellsandt, E., Gardinier, E. S., Manal, K., Axe, M. J., Buchanan, T. S., & Snyder-Mackler, L. (2016). Decreased knee joint loading associated with early knee osteoarthritis after anterior cruciate ligament injury. *The American Journal of Sports Medicine, 44*(1), 143-151.

Wiggins, A. J., Grandhi, R. K., Schneider, D. K., Stanfield, D., Webster, K. E., & Myer, G. D. (2016). Risk of secondary injury in younger athletes after anterior cruciate ligament reconstruction: a systematic review and meta-analysis. *The American Journal of Sports Medicine*, *44*(7), 1861-1876.

Wilson, H. (2008). Becoming 'patient-centred': a review. *NZ Fam Pract, 35*(3), 164-170.

Wilson, I. B., & Cleary, P. D. (1995). Linking clinical variables with health-related quality of life. *Jama, 273*(1), 59-65.

Woo, S. L., & Adams, D. J. (1990). The tensile properties of human anterior cruciate ligament (ACL) and ACL graft tissues *Knee Ligaments: Structure, Function, Injury, and Repair* (pp. 279-289): Raven, New York, NY.

Wu, G., Siegler, S., Allard, P., Kirtley, C., Leardini, A., Rosenbaum, D., Witte, H. (2002). ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion—part I: ankle, hip, and spine. *Journal of Biomechanics, 35*(4), 543-548.

Xergia, S., Pappas, E., & Georgoulis, A. D. (2015). Association of the single-limb hop test with isokinetic, kinematic, and kinetic asymmetries in patients after anterior cruciate ligament reconstruction. *Sports Health, 7*(3), 217-223.

Xergia, S. A., McClelland, J. A., Kvist, J., Vasiliadis, H. S., & Georgoulis, A. D. (2011). The influence of graft choice on isokinetic muscle strength 4–24 months after anterior cruciate ligament reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy, 19*(5), 768-780.

Yasuda, K., Ohkoshi, Y., Tanabe, Y., & Kaneda, K. (1991). Muscle weakness after anterior cruciate ligament reconstruction using patellar and quadriceps tendons. *Bulletin of the Hospital for Joint Diseases Orthopaedic Institute*, 51(2), 175-185.

Zabala, M. E., Favre, J., Scanlan, S. F., Donahue, J., & Andriacchi, T. P. (2013). Three-dimensional knee moments of ACL reconstructed and control subjects during gait, stair ascent, and stair descent. *Journal of Biomechanics*, *46*(3), 515-520.

Zaffagnini, S., Grassi, A., Serra, M., & Marcacci, M. (2015). Return to sport after ACL reconstruction: how, when and why? A narrative review of current evidence. *Joints, 3*(1), 25.

Zantop, T., Brucker, P. U., Vidal, A., Zelle, B. A., & Fu, F. H. (2007). Intraarticular rupture pattern of the ACL. *Clinical Orthopaedics and Related Research, 454*, 48-53.

List of appendices

Chapter 3	Modified Downs and Black scale (Appendix A) Mean difference for peak knee angles for participants with ACLR and Control group.
Chapter 4	Data provided by ACC (Appendix C) Reliability table for KT-arthrometer. Torque and weight data of the participants with ACLR (Appendix- C8).
Chapter 5	Bracket (Appendix D) Participants’ additional quotes Data check with the participants for the qualitative study results
Chapter 6	Data related to surgery provided by ACC and participants (Appendix- C7) Peak torque and weight data of participants with ACLR (Appendix- C8) Time between injury and surgery (Appendix- C9) Pipeline for generate the discrete variables through Visual 3D. (Appendix E) MATLAB script for generating the linear envelops for the angles and moments.
Chapter 7	Assumptions of Multiple regression analysis for stair ascent and descent (Appendix- F1). Assumptions of Multiple regression analysis for stair descent (Appendix- F2).

Appendix A1- Modified from Downs and Black

Methodological quality assessment, modified from Downs and Black

Category	Question number in Downs and Black	Question	Application to this review
Reporting	1.	1. Is the hypothesis/aim/objective of the study clearly described?	Score of "1" if hypothesis/aim/objective described. "0" for no description.
	2.	2. Are the main outcomes to be measured clearly described in the introduction or methods section?	Score of "1" if main outcome measures described in introduction or methods. "0" for no description.
	3.	3. Are the characteristics of the patients included in the study clearly described?	ACLR group: Clear inclusion and exclusion criteria; Control group: No history of surgery, knee injury or pathology; Score of "1" for yes; "0" for no defined criteria's.
	5.	4. Are the distributions of principal confounders for each group to be compared clearly described?	Age, BMI, gender, footwear, sports activity (Tegner score) were considered the main confounders. If 4 of these were specified: score of "2" If 2 of these were specified: score "1" If 1 or none of these were specified: score "0"
	6.	5. Are the main findings of the study clearly described?	Score of "1" if main findings clearly described. Score "0" for no description.
	7.	6. Does the study provide estimates of the random variability in the data for the main outcomes?	SD, SE, CI were considered for measures of variability. Score of "1" if any of these measures of variability given. Score "0" for no description of measures of variability.
	10.	7. Have actual probability values been reported (e.g. 0.035 rather than <0.05) for the main outcomes except where probability value is less than 0.001?	Score of "1" if actual probability values described. Score "0" for no description.
External validity	11.	8. Were the subjects asked to participate in the study representative of the entire population from which they were recruited?	Score of "1" if participants recruited were from the community. Score "0" for no description or if the participants were from a single hospital.
	12.	9. Were those subjects who were prepared to participate representative of the entire population from which they were recruited?	Score of "1" if participants who contacted were from the community and the cohort was finalised from this community based population based on the inclusion criteria. Score "0" for no description.

Category	Question number in Downs and Black	Question	Application to this review
Internal validity bias	15.	10. Was an attempt made to blind those measuring main outcomes of the intervention?	Score of “1” given if blinding done during data processing. Score “0” for no description.
	16.	11. If any of the results of the study were based on “data dredging”, was this made clear?	Score of “1” for clearly mentioning the outcome measures planned. Score “0” if data dredging was there.
	18.	12. Were the statistical tests used to assess the main outcomes appropriate?	Score of “1” if appropriate statistical tests used. Score “0” for no description.
	20.	13. Were the main outcome measures used accurate (valid and reliable)?	Score of “1” if reference given for reliability or validity of the outcome measures used. Score “0” for no description.
Internal validity: selection bias	21.	14. Were the participants of the two groups recruited from the same population?	It was considered important that groups were matched for age (within a mean of 5 years), BMI, sports, gender. Score of “1” if BMI, sports level and gender matched in both groups. Score “0” for no description.
	25.	15. Was there adequate adjustment for the confounding in the analysis from which the findings were drawn?	A score of “1” was applied If speed of gait was not significantly different between groups, alternatively if this was considered a confounding factor in the statistical analysis and score of “0” for no description.
Power	27.	16. Were appropriate power calculations reported?	A score of “1” was applied when a power or a sample size calculation was provided. If these were not given or there was no explanation whether the number of participants was appropriate a “0” was applied.

ACLR: Anterior cruciate ligament reconstruction; BMI: Body mass index; CI: Confidence interval; SD: Standard deviation; SE: Standard error;

Appendix A2- Mean differences for peak knee angles between participants with ACLR for between- and within-group comparisons

Variable (angles)	Task	Comparison	Level of evidence	Studies	MD (95%CI)
Flexion	Walking	Controls	Strong	Four LR (Georgoulis et al., 2003; Hall et al., 2012; Noehren et al., 2013; Webster et al., 2005), two HR (Ferber et al., 2002; Lewek et al., 2002) studies; $I^2 = 58\%$, p=0.04	MD -0.6° (-2.0 to 0.8)
		Contralateral limbs	Moderate	Four LR (Di Stasi et al., 2013; Hall et al., 2012; Roewer et al., 2011; Webster, Feller, et al., 2012) , one HR (Hooper et al., 2001); I^2= 84%, p <0.001	MD -4.3° (-5.5 to -3.2)
	Stair ascent	Controls	Moderate	Two LR (Gao et al., 2012; Hall et al., 2012) studies; I^2= 8%, p=0.30	MD -0.5° (-3.2 to 2.3)
		Contralateral limbs	Limited	One LR (Hall et al., 2012) study	MD -1.2° (-5.1 to 2.7)
	Stair descent	Controls	Moderate	Two LR (Gao et al., 2012; Hall et al., 2012) studies; I^2= 66%, p=0.08	MD -2.7° (-4.7 to -0.7)
	Running	Controls	Moderate	One LR (Noehren et al., 2013), one HR (Lewek et al., 2002) studies; I^2=44%, p=0.44	MD -2.4°(-5.3 to 0.5)
Adduction	Walking	Controls	Moderate	Three LR (Butler et al., 2009; Georgoulis et al., 2003; Webster & Feller, 2012a) studies; I^2 = 73%, p = 0.03	MD -1°(-1.7 to 0.7)
Tibial external rotation	Walking	Controls	Strong	Three LR (Czamara et al., 2015; Georgoulis et al., 2003; Wang et al., 2013) studies; I^2=64%, p = 0.06	MD 1.8° (0.10 to 3.6)
	Stair ascent	Controls	Limited	One LR (Gao et al., 2012) study	MD -3.7° (-8.1 to 0.7)
	Stair descent	Controls	Limited	One LR (Gao et al., 2012) study	MD -5.8° (-9.8 to -1.8)
Tibial internal rotation	Walking	Contralateral limbs	Strong	Three LR (Sato et al., 2013; Webster & Feller, 2011; Webster, Feller, et al., 2012) studies; I^2= 0%, p=0.63	MD-3.9° (-5.8 to -2)
	Stair ascent	Controls	Limited	One LR (Gao et al., 2012) study	MD 2.9° (-1.1 to 6.8)
	Stair descent	Controls	Limited	One LR (Gao et al., 2012) study	MD 3.2° (-1 to 7)

Running	Contralateral limbs	Limited	One LR (Sato et al., 2013) study	MD -5.3° (-10 to 0.7)

HR: High risk of bias; LR: Low risk of bias; MD: Mean difference

Appendix B1- Final ethics approval letter from the ethical committee

UNIVERSITY of OTAGO
Te Whare Wānanga o Otāgo
NEW ZEALAND

H15/034

Academic Services
Manager, Academic Committees, Mr Gary Witte

Dr G Sole

27 May 2015

School of Physiotherapy

Dear Dr Sole,

I am again writing to you concerning your proposal entitled "**Outcomes of anterior cruciate ligament reconstructions more than two years following surgery**", Ethics Committee reference number **H15/034**.

Thank you for your memo of 25th May 2015 addressing the issues raised by the Committee.

The Committee thanks you for the further comment provided in respect of the issues raised in relation to confounding variables. The Committee also note the revised Information Sheet and the addition of the shortened advert to be used for local newspapers.

On the basis of this response, I am pleased to confirm that the proposal now has full ethical approval to proceed.

The standard conditions of approval for all human research projects reviewed and approved by the Committee are the following:

Conduct the research project strictly in accordance with the research proposal submitted and granted ethics approval, including any amendments required to be made to the proposal by the Human Research Ethics Committee.

Inform the Human Research Ethics Committee immediately of anything which may warrant review of ethics approval of the research project, including: serious or unexpected adverse effects on participants; unforeseen events that might affect continued ethical acceptability of the project; and a written report about these matters must be submitted to the Academic Committees Office by no later than the next working day after recognition of an adverse occurrence/event. Please note that in cases of adverse events an incident report should also be made to the Health and Safety Office:

http://www.otago.ac.nz/healthandsafety/ind
ex.html

Advise the Committee in writing as soon as practicable if the research project is discontinued.

Make no change to the project as approved in its entirety by the Committee, including any wording in any document approved as part of the project, without prior written approval of the Committee for any change. If you are applying for an amendment to your approved research, please email your request to the Academic Committees Office:

gary.witte@otago.ac.nz

jo.farrondediaz@otago.ac.nz

Approval is for up to three years from the date of this letter. If this project has not been completed within three years from the date of this letter, re-approval or an extension of approval must be requested. If the nature, consent, location, procedures or personnel of your approved application change, please advise me in writing.

Yours sincerely,

Mr Gary Witte
Manager, Academic Committees
Tel: 479 8256
Email: gary.witte@otago.ac.nz

c.c. Professor G D Baxter Dean School of Physiotherapy

Appendix B2- Amendment letter to the ethical committee

UNIVERSITY OF OTAGO HUMAN ETHICS COMMITTEE AND

UNIVERSITY OF OTAGO HUMAN ETHICS COMMITTEE (HEALTH)

REQUEST FOR EXTENSION OR AMENDMENT TO A PREVIOUSLY APPROVED STUDY

If the nature, content, location, procedure (including recruitment of participants) or personnel (including student investigators) of an application approved by the University of Otago Human Ethics Committee or University if Otago Human Ethics Committee (Health) changes, applicants are responsible for informing the Committee of those changes.

Application Reference number (e.g H13/011, 13/131, D13/001):	H15/034	**Name of University of Otago staff member responsible for the project:**	Dr Gisela Sole
Title of Project:	Outcomes of anterior cruciate ligament reconstructions more than two years following surgery		

Please detail the amendment(s) you would like to make to your approved proposal, the reasons for the change(s), and any additional ethical considerations:

Dear Gary

We have had a slow recruitment outcome for the above study and would like to expand on our strategies. We indicated in the initial application that we would use the School of Physiotherapy Clinics Facebook page, besides sending information to sports and community clubs, physiotherapists and GPs.

We are hereby seeking approval to expand our recruitment via Facebook, particularly those pages frequented by University students (such as the Student Flatting page), and the community page MoveMe, which encourages physical activity.

The wording would remain the same as previously approved (attached) and there would be no other changes.

Kind regards

GSole

Appendix B3- Approval letter from the ethical committee to the amendment letter

H15/034

Academic Services
Manager, Academic Committees, Mr Gary Witte

---

29 February 2016

Dr G Sole
School of Physiotherapy

Dear Dr Sole,

I am again writing to you concerning your proposal entitled **"Outcomes of anterior cruciate ligament reconstructions more than two years following surgery"**, Ethics Committee reference number **H15/034**.

Thank you for your request for amendment of 24th February 2016 indicating that you wish to amend the recruitment process for the above study by advertising on Facebook and the community page MoveMe. The Committee notes that you also intend to e-mail staff and postgraduate students to advertise the study and understands that you have received authorisation from Karyn Thomson, Director of Student Services, to use the distribution list for this purpose.

The Committee accepts and approves the amendment requested.

Your proposal continues to be fully approved by the Human Ethics Committee. If the nature, consent, location, procedures or personnel of your approved application change, please advise me in writing. I hope all goes well for you with your upcoming research.

Yours sincerely,

Mr Gary Witte
Manager, Academic Committees
Tel: 479 8256
Email: gary.witte@otago.ac.nz

c.c. Professor L A Hale Dean School of Physiotherapy

Appendix B4- Research consultation with Maori committee

NGĀI TAHU RESEARCH CONSULTATION COMMITTEE

TE KOMITI RAKAHAU KI KAI TAHU

Tuesday, 19 August 2014.

Dr Gisela Sole,
School of Physiotherapy,
DUNEDIN.

Tena Koe Dr Gisela Sole,

Outcomes of ACL reconstructions

The Ngai Tahu Research Consultation Committee (the committee) met on Tuesday, 19 August 2014 to discuss your research proposition.

By way of introduction, this response from The Committee is provided as part of the Memorandum of Understanding between Te Rūnanga o Ngāi Tahu and the University. In the statement of principles of the memorandum it states "Ngai Tahu acknowledges that the consultation process outline in this policy provides no power of veto by Ngāi Tahu to research undertaken at the University of Otago". As such, this response is not "approval" or "mandate" for the research, rather it is a mandated response from a Ngāi Tahu appointed committee. This process is part of a number of requirements for researchers to undertake and does not cover other issues relating to ethics, including methodology they are separate requirements with other committees, for example the Human Ethics Committee, etc.

Within the context of the Policy for Research Consultation with Māori, the Committee base consultation on that defined by Justice McGechan:

"Consultation does not mean negotiation or agreement. It means: setting out a proposal not fully decided upon; adequately informing a party about relevant information upon which the proposal is based; listening to what the others have to say with an open mind (in that there is room to be persuaded against the proposal); undertaking that task in a genuine and not cosmetic manner. Reaching a decision that may or may not alter the original proposal."

The Committee considers the research to be of importance to Māori health.

As this study involves human participants, the Committee strongly encourage that ethnicity data be collected as part of the research project. That is the questions on self-identified ethnicity and descent, these questions are contained in the latest census.

The Committee suggests dissemination of the research findings to relevant Maori health organisations regarding this study, including Tueora Tinana, Maori Physiotherapists within the New Zealand Society of Physiotherapists.

We wish you every success in your research and the committee also requests a copy of the research findings.

The Ngāi Tahu Research Consultation Committee has membership from:

Te Rūnanga o Ōtākou Incorporated
Kāti Huirapa Rūnaka ki Puketeraki
Te Rūnanga o Moeraki

Appendix B5- Study flyer for recruiting the participants through Newspaper

Research Study

ACL surgery and rehabilitation of the knee

Seeking men and women (aged 20 – 50) to participate in this study:

- **Who have injured their ACL, and underwent reconstructive surgery between 2 to 15 years ago; or**
- **Uninjured participants, who have not had a knee injury that required health professional care**

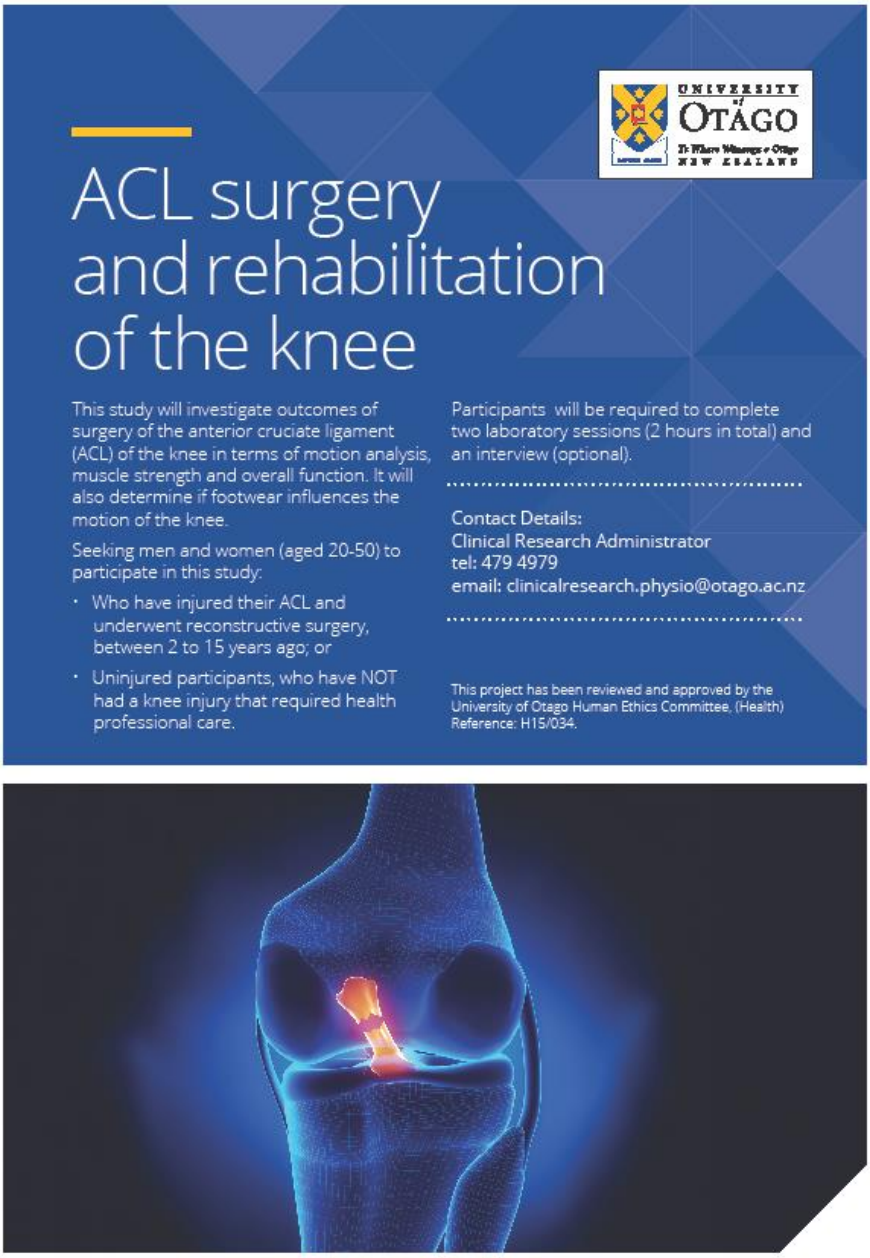
Participants will be required to complete two laboratory sessions (2 hours in total) and an interview (optional).

For more information contact the Clinical Research Administrator:
479 4979
clinicalresearch.physio@otago.ac.nz

This project has been reviewed and approved by the University of Otago Human Ethics Committee (Health). Reference: H15/084

OTAGO

Appendix B6- Study flyer for participants recruitment from community



Appendix B7- Participant information sheet for ACLR group

Participants with ACL reconstructions

Study title:	OUTCOMES OF ACL RECONSTRUCTION MORE THAN 2 YEARS FOLLOWING SURGERY.	
Principal investigator:	**Dr. Gisela Sole** **School of Physiotherapy** **Senior Lecturer**	03-479 7936 Gisela.sole@otago.ac.nz

Introduction

Thank you for showing an interest in this project. Please read this information sheet carefully. Take time to consider and, if you wish, talk with relatives or friends, before deciding whether or not to participate. If you decide to participate we thank you. If you decide not to take part there will be no disadvantage to you and we thank you for considering our request.

What is the aim of this research project?

If you had surgery on an injury of your anterior cruciate ligament (ACL) in your knee more than two years ago, we would like to know how you are moving now when you walk up and down two steps, and when landing after a jump. We also want to assess how far you can jump on each leg, and your thigh muscle strength. We would like to see if there is a difference in your movements when you walk up and down steps with, and without, shoes on. Finally, we would like to know if and how your knee injury has affected your life. Part of this project is the PhD research of Mandeep Kaur.

Who is funding this project?

This study has funding from Physiotherapy New Zealand, and from the Mark Steptoe Memorial Trust Research Grant-in-Aid (School of Physiotherapy).

Who are we seeking to participate in the project?

We need three groups of participants: (1) people who have injured an ACL and had surgery followed by physiotherapy rehabilitation, 2 to 8 years ago; (2) people who injured an ACL, had surgery, and had physiotherapy rehabilitation, 10 to 15 years ago; and (3) uninjured people (the control group).

<u>Inclusion criteria for participants with ACL reconstructions:</u>

- Age: 20-50 years old, men and women;
- No other major injury to the legs and lower back that needed treatment by a health care professional in the last 12 months.

All participants will be offered a voucher to contribute towards travel costs to the School of Physiotherapy in Dunedin.

If you participate, what will you be asked to do?

You will be asked to attend two laboratory sessions for data collection at the School of Physiotherapy, Dunedin. You may also be asked to attend a one-hour interview with the researchers. You are welcome to bring a support person with you to any of the sessions.

<u>Session 1:</u> This session will last about 1½ hours. During this session you will be asked to:

- Complete a questionnaire about your current physical activity and your knee injury. This will take about 15 minutes. You can do this online before the laboratory session if you prefer. We will send you the electronic link by e-mail.
- Bring your own sports, running, or recreational shoes for us to assess for wear.
- If you had an injury, complete a release form for ACC to confirm the date of your knee injury, the date and MRI report (if you had one), the date and type of surgery you had, the number of physiotherapy sessions you attended for rehabilitation, and the date of the last session.
- Undergo a routine screening examination of knee, hip, and ankle by the student researcher to confirm that you are eligible to take part in the study, and to have your weight and height measured.
- Perform practice trials of walking up and down two steps, and jumping forward on each leg to make sure that these movements do not cause pain or discomfort.
- Undergo an examination of the knee to measure laxity of the ligaments.
- Perform five trials of walking up and down the steps, and jumping forward on each leg. Participants with ACL reconstructions 2 to 8 years ago will walk up and down the steps (1) barefoot and (2) with their own sports shoes. Participants with ACL reconstructions 10 to 15 years ago will perform the stair ascent/descent only in their sports shoes. The jumping task will be performed with your own sports shoes.

Your movements will be recorded and measured using 3D motion analysis equipment. We will place a set of small reflective markers on your skin, and on the clothing on your legs, pelvis, trunk, and arms, using double-sided tape. A video will also be made with a digital recorder during the stair ascent/descent and the jumping trials in case the researchers need to check your movements later. This video will not be used for any other purpose.

Session 2:

This session will last about 45 minutes. Following a warm-up, you will be asked to jump as far as you can, three times on each leg. Your thigh muscle strength will then be measured: you will be asked to straighten and bend your knee as hard as you can five times against the measuring machine's lever. This will be performed for both legs. The result of the thigh muscle strength test will be given to you as soon as you have finished this session.

Session 3:

Approximately 10 injured participants will be recruited for this part of the study, a face-to-face one-hour interview with Ms Mandeep Kaur and Dr Sole. If you agree to be interviewed, and live outside Dunedin, the interview can be conducted via Skype or telephonically, at a time that suits you best.

If you live outside Dunedin, all three sessions can take place on the same day if you wish. The laboratory sessions will last up to 2¼ hrs, and the interview will be an additional hour if you agree to do this. In this case, we will provide you with refreshments.

The interview will be tape-recorded and the interviewers may make notes. The questions will be about how well you have recovered from your injury and the surgery in terms of your daily life. The precise nature of the questions has not been determined in advance, but will depend on the way in which the interview develops. In the event that the line of questioning develops in such a way that you feel hesitant or uncomfortable, you may decline to answer any particular question(s) without any disadvantage. A summary of the results of all of the interviews will be emailed or posted to you, and you can correct or add anything if you wish.

Is there any risk of discomfort or harm from participation?

There is no risk of physical harm or discomfort to you. You may feel a bit sore after the muscle strength test, as you might in any strengthening exercise programme. You may contact the researchers if you have any concerns about that muscle soreness, or if you have any other questions.

What data or information will be collected, and how will they be used?

We will collect the following information:

- Your name and date of birth; weight, height, ethnicity, leg dominance;
- Your level of physical activity, now and prior to the knee injury; confidence in your knee during sport; and your general quality of life.
- Movement analysis data during the stair ascent/descent and jump landing; the jump distance and thigh muscle strength for each leg

We will use this information to describe the groups of participants and compare with healthy control group.

What about anonymity and confidentiality?

All data and the recordings will be securely stored in such a way that only Dr Sole, Dr Ribeiro, Ms Kaur and a designated Research Assistant will be able to gain access to it. Data obtained as a result of the research will be kept in secure storage for at least 10 years. Any personal information held about the participants (such as contact details, audio files after they have been transcribed, and video files) will be destroyed at the completion of the research except as required by university's policy. Information used for any publication will be kept anonymous.

The results for the footwear study (barefoot versus shod during stair ascent/descent) will be written up as an individual study by the principal investigator and submitted for publication. The results of the remaining studies will be written up as Ms Mandeep's research towards her doctorate degree and may be published. It will be available in the University of Otago Library (Dunedin, New Zealand).

If you agree to participate, can you withdraw later?

You may withdraw from participation in the project at any time and without any disadvantage to yourself of any kind. If you agree to take part in the interview and the line of questioning develops in such a way that you feel hesitant or uncomfortable, you may decline to answer any particular question(s), and/or may withdraw from the project without disadvantage of any kind. Your future health care provision will not be affected by participating in the study, or by withdrawing or declining.

Any questions?

If you have any questions now or in the future, please feel free to contact either:

Clinical Research Administrator **School of Physiotherapy**	Tel: 03-479 4979
Dr. Gisela Sole	Tel: 03 479 7936

Senior Lecturer **School of Physiotherapy**	gisela.sole@otago.ac.nz
Dr. Daniel Cury Ribeiro **Lecturer** **School of Physiotherapy**	Tel: 03 479 7455 daniel.ribeiro@otago.ac.nz
Mandeep Kaur **PhD candidate, student researcher** **School of Physiotherapy**	mandeep.kaur@otago.ac.nz

This study has been approved by the University of Otago Human Ethics Committee (Health), Ref. no. H15/034. If you have any concerns about the ethical conduct of the research you may contact the Committee through the Human Ethics Committee Administrator (phone +64 3 479 8256 or email gary.witte@otago.ac.nz). Any issues you raise will be treated in confidence and investigated and you will be informed of the outcome.

Appendix B8- Participant information sheet for control group

Study title:	**OUTCOMES OF ACL RECONSTRUCTION MORE THAN 2 YEARS FOLLOWING SURGERY.**	
Principal investigator:	**Dr. Gisela Sole** **School of Physiotherapy** **Senior Lecturer**	03-4797936 gisela.sole@otago.ac.nz

Introduction

Thank you for showing an interest in this project. Please read this information sheet carefully. Take time to consider and, if you wish, talk with relatives or friends, before deciding whether or not to participate. If you decide to participate we thank you. If you decide not to take part there will be no disadvantage to you and we thank you for considering our request.

What is the aim of this research project?

We would like to know whether people who have had surgery (reconstruction) to the anterior cruciate ligament (ACL) in the knee move differently compared to uninjured people while walking up and down a set of steps and when landing after a jump. We also want to see how far people with an ACL reconstruction can jump on each leg compared to uninjured people, and how strong the thigh muscles are. Lastly, we would like to see if there is a difference in your movements when you walk up and down steps with, and without, shoes on. Part of this project is the PhD research of Mandeep Kaur.

Who is funding this project?

This study has funding from Physiotherapy New Zealand, and from the Mark Steptoe Memorial Trust Research Grant-in-Aid (School of Physiotherapy).

Who are we seeking to participate in the project?

We need three groups of participants: (1) people who have injured an ACL and had surgery followed by physiotherapy rehabilitation, 2 to 8 years ago; (2) people who injured an ACL, had surgery, and had physiotherapy rehabilitation, 10 to 15 years ago; and (3) uninjured people (the control group).

Inclusion criteria for control participants:

- Age: 20-50 years old, and both men and women;
- No major injury to either legs or lower back that needed treatment by a health care professional in the past 12 months.

All participants will be offered a voucher to contribute towards travel costs to the School of Physiotherapy in Dunedin.

If you participate, what will you be asked to do?

You will be asked to attend two laboratory sessions for data collection at the School of Physiotherapy, Dunedin. You are welcome to bring a support person with you to any of the sessions.

Session 1: This session will last about 1½ hours. During this session you will be asked to:

- Complete a questionnaire about your current physical activity and knee-related health. This will take about 15 minutes. You can do this online before the laboratory session if you prefer. We will send you an electronic link by e-mail.
- Bring your own sports, running, or recreational shoes for us to assess for wear.
- Undergo a routine screening examination of knee, hip, and ankle by the student researcher to confirm that you are eligible to take part in the study, and to have your weight and height measured.
- Perform practice trials of walking up and down two steps, and jumping forward on each leg.
- Undergo an examination of the knee to measure the laxity of the ligaments.
- Walk up and down a set of steps, and jump forward on each leg. You will be asked to walk up and down the steps (1) barefoot and (2) with your own sports shoes. You will do this five times for each leg (for each footwear condition). You will perform the jumping tasks with your own sports shoes, five trials for each leg.

Your movements will be recorded and measured using 3D motion analysis equipment. We will place a set of small reflective markers on your skin, and on the clothing on your legs, pelvis, trunk, and arms, using double-sided tape. A video will also be made with a digital recorder during the stair ascent/descent trials and the jumping trials in case the researchers need to check your movements later. This video will not be used for any other purpose.

Session 2:

This session will last about 45 minutes.

Following the warm up, you will be asked to jump as far as you can and land on the same leg (three times on each side). Your thigh muscle strength will then be measured: you will be asked to straighten and bend your knee as hard as you can five times against the measuring machine's lever. This will be performed for both legs. The result of the thigh muscle strength test will be given to you as soon as you have finished this session.

If it suits you better, both sessions can be performed on the same day. The laboratory sessions will be a total of 2 ¼ hrs. Refreshments will be provided by the researchers in this case.

Is there any risk of discomfort or harm from participation?

There is no risk of physical harm or discomfort to you. You may feel a bit sore after the muscle strength test, as you might in any strengthening exercise programme. You may contact the researchers if you have any concerns about that muscle soreness, or if you have any other questions.

What data or information will be collected, and how will they be used?

We will collect the following information:

- Your name and date of birth; weight, height, ethnicity, leg dominance;
- Your level of physical activity; confidence in your knee during sport; and your general quality of life.
- Movement analysis data during the stair ascent/descent and jump landing; the jump distance and thigh muscle strength for each leg

We will use this information to describe the groups of participants and to compare with the ACL reconstructed group.

What about anonymity and confidentiality?

All the data and the recordings will be securely stored in such a way that only Dr Sole, Dr Ribeiro, Ms Kaur and a designated Research Assistant will be able to gain access to it. Data obtained as a result of the research will be kept in secure storage for at least 10 years. Any personal information held about the participants (such as contact details, audio files after they have been transcribed, and video files) will be destroyed at the completion of the research except as required by university's research policy. Information used for any publication will be kept anonymous.

The results for the footwear study (barefoot versus shod during stair ascent/descent) will be written up as an individual study by the principal investigator and submitted for publication. The results of the remaining studies will be written up as Ms Mandeep's research towards her doctorate degree and may be published. It will be available in the University of Otago Library (Dunedin, New Zealand).

If you agree to participate, can you withdraw later?

You may withdraw from participation in the project at any time and without any disadvantage to yourself of any kind. Your future health care provision will not be affected by participating in the study, or by withdrawing or declining.

Any questions?

If you have any questions now or in the future, please feel free to contact either:

Clinical Research Administrator **School of Physiotherapy**	Tel: 03-479 4979 clinicalresearch.physio@otago.ac.nz
Dr. Gisela Sole **Senior Lecturer** **School of Physiotherapy**	Tel: 03 479 7936 gisela.sole@otago.ac.nz
Dr. Daniel Cury Ribeiro **Lecturer** **School of Physiotherapy**	Tel: 03 479 7455 daniel.ribeiro@otago.ac.nz
Mandeep Kaur **PhD candidate, student researcher** **School of Physiotherapy**	mandeep.kaur@otago.ac.nz

This study has been approved by the University of Otago Human Ethics Committee (Health), Ref. no. H15/034. If you have any concerns about the ethical conduct of the research you may contact the Committee through the Human Ethics Committee Administrator (phone +64 3 479 8256 or email gary.witte@otago.ac.nz). Any issues you raise will be treated in confidence and investigated and you will be informed of the outcome.

Appendix B9- Consent form for ACLR group

CONSENT FORM FOR PARTICIPANTS with ACL RECONSTRUCTIONS

Principal Investigator: Dr Gisela Sole; gisela.sole@otago.ac.nz

Following signature and return to the research team this form will be stored in a secure place for ten years.

Name of participant:…………………………………………..

1. I have read the Information Sheet concerning this study and understand the aims of this research project.
2. I have had sufficient time to talk with other people of my choice about participating in the study.
3. I confirm that I meet the criteria for participation which are explained in the Information Sheet.
4. All my questions about the project have been answered to my satisfaction, and I understand that I am free to request further information at any stage.
5. I know that my participation in the project is entirely voluntary, and that I am free to withdraw from the project at any time without disadvantage.
6. I know that as a participant, small markers will be placed on my trunk and legs and I will be required to walk up and down a stair (5 times), and perform five jumps on each leg during Session one. During Session 2 I will be asked three times as far as I can on each leg and my thigh muscle strength will be measured with a Biodex machine by bending and straightening the leg. If I feel hesitant or uncomfortable I can withdraw at any point of the time.
7. If I agree, I may also choose to participate in an individual interview with the researchers. The general line of questioning includes outcomes of my knee surgery related to my health-related quality of life. The precise nature of the questions which will be asked has not been determined in advance, but will depend on the way in which the interview develops. In the event that the line of questioning develops in such a way that I feel hesitant or uncomfortable I may decline to answer any particular question(s) and/or may withdraw from the project without disadvantage of any kind.

8. I grant the researchers permission to contact ACC to confirm the date of my injury, date and report of MRI (if applicable), date and procedure of the surgery I underwent, the number of physiotherapy treatments I had for the knee, and the date of the last physiotherapy treatment.
   Yes ☐ No ☐ (please indicate Yes or No)
9. I understand the nature and size of the risks of discomfort or harm which are explained in the Information Sheet.
10. I know that when the project is completed all personal identifying information will be removed from the paper records and electronic files which represent the data from the project, and that these will be placed in secure storage and kept for at least ten years.
11. I understand that the results of the project may be published and be available in the University of Otago Library, but that any personal identifying information will remain confidential between myself and the researchers during the study, and will not appear in any spoken or written report of the study.

12. I know that there is no remuneration offered for this study, and that no commercial use will be made of the data. After participating in the study I will be offered a petrol voucher in recognition of costs associated with participation in the study.

Signature of participant:	Date:

Appendix B10- Consent form for control group

OUTCOMES OF ACL RECONSTRUCTION MORE THAN 2 YEARS FOLLOWING SURGERY.

CONSENT FORM FOR CONTROL PARTICIPANTS

Principal Investigator: Dr Gisela Sole; gisela.sole@otago.ac.nz

Following signature and return to the research team this form will be stored in a secure place for ten years.

Name of participant:…………………………………………..

1. I have read the Information Sheet concerning this study and understand the aims of this research project.
2. I have had sufficient time to talk with other people of my choice about participating in the study.
3. I confirm that I meet the criteria for participation which are explained in the Information Sheet.
4. All my questions about the project have been answered to my satisfaction, and I understand that I am free to request further information at any stage.
5. I know that my participation in the project is entirely voluntary, and that I am free to withdraw from the project at any time without disadvantage.
6. I know that as a participant, small markers will be placed on my trunk and legs and I will be required to walk up and down a stair (5 times), and perform five jumps on each leg during Session one. During Session 2 I will be asked three times as far as I can on each leg and my thigh muscle strength will be measured with a Biodex machine by bending and straightening the leg. If I feel hesitant or uncomfortable I can withdraw at any point of the time.
7. I understand the nature and size of the risks of discomfort or harm which are explained in the Information Sheet.
8. I know that when the project is completed all personal identifying information will be removed from the paper records and electronic files which represent the data from the project, and that these will be placed in secure storage and kept for at least ten years.

9. I understand that the results of the project may be published and be available in the University of Otago Library, but that any personal identifying information will remain confidential between myself and the researchers during the study, and will not appear in any spoken or written report of the study.

10. I know that there is no remuneration offered for this study, and that no commercial use will be made of the data. After participating in the study I will be offered a petrol voucher in recognition of costs associated with participation in the study.

Signature of participant: Date:

Appendix B11- ACC release form

Study title:	OUTCOMES OF ACL RECONSTRUCTION, MORE THAN 2 YEARS FOLLOWING SURGERY.	
Principal investigator:	**Dr. Gisela Sole** **School of Physiotherapy** **Senior lecturer**	03-4797936 gisela.sole@otago.ac.nz

Name of participant: ______________________________________

Date of Birth: ____

Address: ____

Telephone number: ____________________________________

I, ___________________________________, give consent to Dr Gisela Sole to obtain from ACC medical information relating to my knee injury.

Date of injury: ______________________, claim number (if available): _________________________.

Participant's signature: _____________________________________ Date: ___________________

TO BE COMPLETED BY ACC:

Date of injury		**Date of MRI (if applicable)**	
Date of surgery:			
Type of surgery	Hamstring graft ◻	Patella tendon graft ◻	Other graft ◻
	Meniscal repair ◻	Partial menisectomy ◻	Menisectomy ◻
Number of physiotherapy treatments pre- surgery			
Number of physiotherapy treatments post-surgery			
Date of last physiotherapy treatment			

ACC: Please attach surgical and MRI reposts, if available.

Appendix C1- Knee Injury and Osteoarthritis Outcome Score (KOOS)

Instructions: This survey asks for your view about your knee. This information will inform us of how you feel about your knee and how well you are able to perform your usual activities.

Please answer every question by circling the appropriate box, only **ONE** box for each question. If you are unsure about how to answer a question, please give the best answer you can.

Symptoms

These questions should be answered thinking of your knee symptoms during the **LAST WEEK.**

S1	**Do you have swelling in your knee?**				
	Never	Rarely	Sometimes	Often	Always
S2	**Do you feel grinding, hear clicking or any other type of noise when your knee moves?**				
	Never	Rarely	Sometimes	Often	Always
S3	**Does your knee catch or hang up when moving?**				
	Never	Rarely	Sometimes	Often	Always
S4	**Can you straighten your knee fully?**				
	Never	Rarely	Sometimes	Often	Always
S5	**Can you bend your knee fully?**				
	Never	Rarely	Sometimes	Often	Always

Stiffness

The following questions concern the amount of joint stiffness you have experienced during the **last week** in your knee. Stiffness is a sensation of restriction or slowness in the ease with which you move your knee joint.

S6	**How severe is your knee joint stiffness after first wakening** in the morning**?**				
	None	Mild	Moderate	Severe	Extreme
S7	**How severe is your knee stiffness after sitting, lying or resting** later in the day**?**				
	None	Mild	Moderate	Severe	Extreme

Pain

P1	**How often do you experience knee pain?**				
	Never	Monthly	Weekly	Daily	Always

What amount of knee pain have you experienced the **LAST WEEK** during the following activities?

P2	**Twisting/pivoting on your knee**				
	None	Mild	Moderate	Severe	Extreme
P3	**Straightening knee fully**				
	None	Mild	Moderate	Severe	Extreme
P4	**Bending knee fully**				
	None	Mild	Moderate	Severe	Extreme
P5	**Walking on flat surface**				
	None	Mild	Moderate	Severe	Extreme
P6	**Going up or down stairs**				
	None	Mild	Moderate	Severe	Extreme
P7	**At night while in bed**				
	None	Mild	Moderate	Severe	Extreme
P8	**Sitting or lying**				
	None	Mild	Moderate	Severe	Extreme
P9	**Standing upright**				
	None	Mild	Moderate	Severe	Extreme

Function, daily living

The following questions concern your physical function. By this we mean your ability to move around and to look after yourself. For each of the following activities please indicate the degree of difficulty you have experienced in the **LAST WEEK** dur to your knee.

A1	**Descending stairs**					
		None	Mild	Moderate	Severe	Extreme
A2	**Ascending stairs**					
		None	Mild	Moderate	Severe	Extreme

For each of the following activities please indicate the degree of difficulty you have experienced in the **LAST WEEK** due to your knee.

A3	**Rising from sitting**					
		None	Mild	Moderate	Severe	Extreme
A4	Standing					
		None	Mild	Moderate	Severe	Extreme
A5	**Bending to floor/pick up an object**					
		None	Mild	Moderate	Severe	Extreme
A6	**Walking on flat surface**					
		None	Mild	Moderate	Severe	Extreme
A7	**Getting in/out of car**					
		None	Mild	Moderate	Severe	Extreme
A8	**Going shopping**					
		None	Mild	Moderate	Severe	Extreme
A9	**Putting on socks/stockings**					
		None	Mild	Moderate	Severe	Extreme
A10	**Rising from bed**					
		None	Mild	Moderate	Severe	Extreme
A11	**Taking off socks/stockings**					
		None	Mild	Moderate	Severe	Extreme

A12	**Lying in bed (turning over, maintaining knee position)**				
	None	Mild	Moderate	Severe	Extreme
A13	**Getting in/out of bath**				
	None	Mild	Moderate	Severe	Extreme
A14	Sitting				
	None	Mild	Moderate	Severe	Extreme
A15	**Getting on/off toilet**				
	None	Mild	Moderate	Severe	Extreme

For each of the following activities please indicate the degree of difficulty you have experienced in the **LAST WEEK** dur to your knee

A16	**Heavy domestic duties (moving heavy boxes, scrubbing floors, etc.)**				
	None	Mild	Moderate	Severe	Extreme
A17	**Light domestic duties (cooking, dusting,)**				
	None	Mild	Moderate	Severe	Extreme

<u>Function, sports and recreational activities</u>

The following questions concern your physical function when being active on a higher level. The questions should be answered thinking of what degree of difficulty you have experienced during the **LAST WEEK** due to your knee.

SP1	**Squatting**				
	None	Mild	Moderate	Severe	Extreme
SP2	Running				
	None	Mild	Moderate	Severe	Extreme
SP3	Jumping				
	None	Mild	Moderate	Severe	Extreme
SP4	**Twisting/pivoting on your injured knee**				

	None	Mild	Moderate	Severe	Extreme
SP5	Kneeling				
	None	Mild	Moderate	Severe	Extreme

Quality of life

SP1	**Squatting**				
	None	Mild	Moderate	Severe	Extreme
SP2	Running				
	None	Mild	Moderate	Severe	Extreme
SP3	Jumping				
	None	Mild	Moderate	Severe	Extreme
SP4	**Twisting/pivoting on your injured knee**				
	None	Mild	Moderate	Severe	Extreme
SP5	Kneeling				
	None	Mild	Moderate	Severe	Extreme

Appendix C2- Tegner activity Scores

Please mark the category below that best reflects your sports (and work) participation (1) at the time of your knee injury and (2) currently.(Briggs et al., 2009)

		When you incurred your knee injury	Current
10	**Competitive Sports** Soccer, rugby: national and international elite		
9	**Competitive Sports** Soccer, rugby (lower divisions), ice hockey, wrestling, gymnastics		
8	**Competitive Sports** Squash, badminton, athletics (jumping), skiing		
7	**Competitive sports** Tennis, athletics (running), motorcross, handball, basketball, netball, cross-country **Recreational sports** Soccer, ice hockey, squash, athletics (jumping), cross-country		
6	**Recreational sports** Tennis and badminton, netball, basketball, skiing, jogging at least five times/week		
5	**Work** Heavy labor (building, forestry, farming) **Competitive Sports** Cycling, cross-country skiing **Recreational sports** Jogging on uneven ground at least twice weekly		
4	**Work** Moderately heavy work (truck driving, heavy domestic work) **Recreational sports** Cycling, cross-country skiing, jogging on even ground at least twice weekly		
3	**Work** Light labor (nursing) **Competitive and recreational sports** Swimming Walking		
2	**Work** Light labour, walking on uneven ground possible but impossible to walk in forest		
1	**Work** Sedentary work, walking on even ground possible		
0	**Sick Leave or Disability due to knee**		

Appendix C3- Confidence during your sport scale

Confidence during your sport

		Not at all	Extremely
1.	**Are you concerned about environmental conditions such as wet playing field, a hard court or the type of gym floor when involved in your sport?**	**0**	**10**
2.	**Do you find it difficult to go “full out” at your sport?**	**0**	**10**
3.	**Do you feel that you risk injury when playing your sport?**	**0**	**10**
4.	**How much effort is it for you to give 100% at your sport?**	**0**	**10**
5.	**How wary are you of injury-provoking situations when playing your sport?**	**0**	**10**
6.	**Do you strap any joints or wear a brace when playing your sport?**	**0**	**10**
7.	**How often do you find yourself being hesitant in your sport participation?**	**0**	**10**
8.	**Are you satisfied with your ability to perform well at your sport?**	**0**	**10**

Appendix C4- Short Form-12 Health Survey

This survey asks for your views about your health. Answer each question by choosing joint one answer. If you are unsure how to answer a question, please give the best answer you can.

1. In general, would you say your health is:				
1 Excellent	2 Very good	3 Good	4 Fair	5 Poor

The following questions are about activities you might do during a typical day. Does your health now limit you in these activities? If so, how much?

		YES, limited a lot	YES, limited a little	NO, not limited at al.
2.	Moderate activities such as moving a table, pushing a vacuum cleaner, bowling or playing golf.	1	2	3
3.	Climbing several flights of stairs.	1	2	3

During the past 4 weeks, have you had any of the following problems with your work or other regular daily activities as a result of your physical health?

		YES	NO
4.	Accomplished less than you would like.	1	2
5.	Were limited in the kind of work or other activities	1	2

During the past 4 weeks, have you had any of the following problems with your work or other regular daily activities as a result of any emotional problems (such as feeling depressed or anxious)?

		YES	NO
6.	Accomplished less than you would like.	1	2
7.	Did work or activities less carefully than usual.	1	2

8. During the past 4 weeks, how much did pain interfere with your normal work (including work outside the home and housework)?

1 Not at all	2 A little bit	3 Moderately	4 Quite a bit	5 Extremely

These questions are about how you have been feeling during the past 4 weeks. For each question, please give the one answer that comes closest to the way you have been feeling.

How much of the time during the past 4 weeks……

		All of the time	Most of the time	A good bit of the time	Some of the time	A little of the time	None of the time
9.	Have you felt calm & peaceful?						
10.	Did you have a lot of energy?						
11.	Have you felt down-hearted and blue?						

12. During the past 4 weeks, how much of the time has your physical health or emotional problems interfered with your social activities (like visiting friends, relatives, etc)?

1 All of the time	2 Most of the time	3 Some of the time	4 A little of the time	5 None of the time

Thank you very much for completing this questionnaire.

Appendix C5- History of previous injuries

For questions 1-5, please circle the relevant box for an injury you have had treatment for **in the past 6 months** and indicate in the box whether the injury was on your left or right. (Participants with ACL injury: detail pertaining to your knee injury will be asked on the following page.)

1.	Have you ever pulled (strained) or hurt a muscle or tendon other than a hamstring?	Back 1	Buttock/pelvis 2	Groin 3	Front of thigh 4	Calf/Achilles 5
2.	Have you ever torn (sprained) or stretched a ligament	Back 6	Buttock 7	Hip 8	Knee 9	Foot/Ankle 10
3.	Have you ever dislocated a joint or had a bone come out of joint?	Back 11	Pelvis 12	Hip 13	Knee 14	Foot/Ankle 15
4.	Have you ever broken (fractured) a bone?	Trunk 16	Pelvis 17	Upper leg 18	Lower leg 19	Foot 20
5.	Have any of your joints ever swollen?	Back 21	Hip 23	Knee 24	Ankle 25	Foot 26
If yes was answered for any question above, please provide detail and date (month, year) and weeks absence from sport due to the injury.						
Are you currently on any prescribed medication? If yes, please provide detail.						

Appendix C6- Reliability of KT-arthrometer in sagittal plane

Participant ID	Side	Session 1 (Average, mm)	Session 2 (Average, mm)
574	1	6.2	6.3
	0	4.9	5.2
251	1	4.9	5.2
	0	9.3	9.3
837	1	5.8	4.4
	0	5.6	7.0
686	1	3.7	6.7
	0	6.6	6.0
116	1	10.7	12.4
	0	8.0	7.6
673	1	5.0	5.5
	0	6.3	6.7
797	1	7.8	10.1
	0	7.4	12.5
449	1	2.2	5.0
	0	6.2	8.3
251	1	5.5	6.1
	0	8.9	8.6
832	1	3.8	3.0
	0	10.5	9.0

AP: Antero-posterior, 1: Right, 0: Left.

Reliability and SEM of KT-Arthrometer

Test measurement	AP-laxity (mm)	
	ICC (95% CI)	**SEM (mm)**
N=10 participants with ACLR		
AP knee laxity	0.84 (0.59-0.93)	2.2

AP: Antero-posterior, SEM: Standard error of measurement, ICC: Intraclass correlation coefficient, ACL: Anterior cruciate ligament, mm= millimetre.

Appendix C7- Data provided by Participants and Accident Compensation Corporation (ACC)

	Participant ID	Accident Date	Date of MRI	Date of Surgery	Type of Surgery	Surgical details (Type of graft, meniscal resection)	Number of Physio treatments Pre-Surgery	Number of Physio treatments Post-Surgery	Date of last physio treatments
Group 1 (ACLR 2-10 years post-operative))									
1.	468					HT, No meniscal resection			
2.	116	4/11/2008	3/05/2010	6/09/2010	KNE81(Primary ACLR)	PT, Meniscectomy	27	48	7/07/2011
3.	844					HT, No meniscal resection			
4.	574	25/10/2009		1/03/2010	Meniscal repair, partial menisectomy, –routine ACLR– bucket handle tear of the medial meniscus.	PT	20	6	26/04/2010
5.	861	27/04/2010	26/05/2010 4/10/2010	4/06/2010 24/03/2011	KNE80 KNE83 Revision ACLR	PT	21	37	12/09/2011
6.	434	5/09/2009	12/11/2009	3/06/2010	KNE80	PT, no meniscal resection	19	14	23/08/2010
7.	686					PT, Menisectomy			
8.	713	16/12/2009		16/12/2011	KNE81 (Primary ACLR)	_	12	1	6/01/2012
9.	832	24/04/2010	21/05/2010	23/11/2010	KNE81 (Primary ACLR)	HT, meniscal resection	25	17	26/01/2012
10.	232	14/04/2012	11/05/2012 28/05/2014	1/11/2012	KNE81 (Primary ACLR)	HT, No meniscal resection	7	5	17/06/2014
11.	251	3/09/2011	1/06/2012	23/07/2012	KNE81(Primary ACLR)	HT	9	23	9/04/2013
12.	451					PT, Partial lateral menisectomy			

	Participant ID	Accident Date	Date of MRI	Date of Surgery	Type of Surgery	Surgical details (Type of graft, meniscal resection)	Number of Physio treatments Pre-Surgery	Number of Physio treatments Post-Surgery	Date of last physio treatments
13.	449	21/05/2011	25/08/2011	16/04/2012	KNE81 (Primary knee ACLR)	HT with meniscal repair			
14.	704	5/02/2011	10/04/2012	16/06/2011	KNE81 (Primary knee ACLR)	HT, Partial Menisectomy	9	40	19/03/2013
15.	608					HT, No meniscal resection			
16.	896					PT, Meniscal repair			
17.	532	13/07/2010	7/10/2010	17/02/2011	KNE81 (Primary ACLR)	HT	8	12	2/09/2011
18.	751	3/10/2012		17/01/2013	Arthroscopic ACLR (L) knee, single bundle with meniscal repair	HT, meniscal repair	2	14	10/05/2013
19.	494	8/05/2010	18/06/2010	16/12/2010	KNE81(Primary ACLR)	HT, no meniscectomy	13	15	28/03/2011
20.	673	9/02/2008	11/04/2008	27/01/2009	KNE80	PT, Meniscal repair	11	23	27/08/2009
21.	837	13/07/2013	7/10/2013	17/12/2013	KNE81 (Primary knee ACLR)	HT , No meniscal resection	19	14	3/03/2014
22.	711	30/04/2011		26/06/2012	KNE91 (Primary ACLR with Meniscal Repair &/or Outerbridge drilling)	HT, Posterior horn lateral meniscus repair.	1	9	8/01/2013
23.	701	10/08/2013	15/10/2013	6/12/2013	KNE81 (Primary ACLR)	HT	10	12	25/03/2014
24.	255	23/05/2009		12/10/2010	KNE81 (Primary knee ACLR)	_	14	18	31/10/2014
25.	408					PT, no meniscal resection			
26.	160	9/09/2005		31/01/2006	ACLR and menisectomy of right knee	Allograft	Unknown	3	5/04/2007

HT: Hamstring tendon, PT: Patellar tendon, MRI: Magnetic resonance imaging, ACLR: Anterior cruciate ligament reconstruction

Appendix C8- Peak torque and weight data of participants with ACLR

	Participant ID	Group	Gender	Mass (kg)	Concentric quadriceps (nm)		Concentric hamstring (nm)		Eccentric quadriceps (nm)	
					Right	Left	Right	Left	Right	Left
1.	468	2	1	80	151.9	148.8	69	76.8	126	135.6
2.	116	2	1	76	98.5	102.3	45.6	48.3	139.1	157
3.	844	2	1	75	148.5	174.6	67.3	88.5	171.2	169.5
4.	574	2	0	98	329.8	312.3	154.8	151.5	410.5	430.6
5.	861	2	1	77	_	_	_	_	_	_
6.	434	2	0	117	243.2	275	136.2	161.5	410.3	390.3
7.	686	2	0	87	143.9	106.8	75.9	67.8	145.8	189.5
8.	713	2	1	71	139.8	132.2	76.7	70.5	255	190.3
9.	832	2	1	62	157.4	154.8	73.7	87.6	165.7	159
10.	232	2	0	67	180.3	171	86.8	79.5	159.6	198.9
11.	251	2	1	68	132.2	98.9	73.1	79.3	188.5	154
12.	451	2	1	76	262.1	193.5	149.8	130	258.9	220.9
13.	449	2	0	89	144.9	67.7	77.6	68.1	210.8	140.7
14.	704	2	1	85	_	_	_	_	_	_
15.	608	2	0	83	238.3	170.5	136.8	134.6	217.8	166.8
16.	896	2	0	77	128.5	114.3	73.1	71.9	0	0
17.	532	2	1	63	253.2	229.2	146.2	112.6	273.4	164.8
18.	751	2	0	75	172.2	185.3	93.9	63.4	187.8	185.8
19.	494	2	0	71	130.1	112.9	78	74.7	103	78.9
20.	673	2	1	86	247.4	230.1	126	117.3	235.9	228.2
21.	837	2	0	94	281.6	290.1	150.3	151	266.3	210.4
22.	711	2	0	85	94.7	89.5	55.7	50.7	105.4	107.9
23.	701	2	1	64	114	86.1	61.3	61	111.3	88.3
24.	255	2	1	60	220.8	277.3	125.2	137.1	292.1	477.5
25.	408	3	0	87	187	219	94.2	147.4	196.4	169.7
26.	789	3	0	86	147.7	196.7	127.2	102.4	262	255.1
27.	634	3	0	86	241.4	235.2	121.1	107.5	268.9	314.1
28.	491	3	0	75	169.8	167.3	111.9	90.2	182.4	185.1
29.	206	3	1	57	_	_	_	_	_	_

	Participant ID	Group	Gender	Mass (kg)	Concentric quadriceps (nm)		Concentric hamstring (nm)		Eccentric quadriceps (nm)	
					Right	Left	Right	Left	Right	Left
30.	797	3	1	71	250.3	183.8	121.4	102.7	271.2	175.1
31.	703	3	1	79	190	156	86.7	93.2	211	116.5
32.	851	3	0	81	128.7	181.7	86.9	86.7	145.6	184.6
33.	467	3	0	79	214.3	187.2	99.9	93.4	273.4	212.3

1: women, 0: men, 2: Participants with ACLR from 2 to 10 years following surgery, 3: Participants with ACLR from 10-20 years following surgery, _: missing data.

Appendix C9-Time between injury and surgery

	Participant ID	Accident Date	Date of Surgery	Time between injury and surgery	Time since ACLR (years)
Group 1 (2 to 10 years post-operative)					
1 1	468	_	_	_	4
2	116	4/11/2008	6/09/2010	23 months	5
3	844	_	_	_	4
4	574	25/10/2009	1/03/2010	6 months	5
5	861	27/04/2010	4/06/2010	2 months	5
6	434	5/09/2009	3/06/2010	9 months	5
7	686	_	_	_	9
8	713	16/12/2009	16/12/2011	24 months	6
9	832	24/04/2010	23/11/2010	7 months	5
10	232	14/04/2012	1/11/2012	7 months	3
11	251	3/09/2011	23/07/2012	12 months	4
12	451	_	_	_	8
13	449	21/05/2011	16/04/2012	10 months	4
14	704	5/02/2011	16/06/2011	4 months	
15	608	_	_	_	9
16	896	_	_	_	2
17	532	13/07/2010	17/02/2011	8 months	4
18	751	3/10/2012	17/01/2013	3 months	2.5
19	494	8/05/2010	16/12/2010	7 months	4
20	673	9/02/2008	27/01/2009	12 months	7
21	837	13/07/2013	17/12/2013	6 months	3
22	711	30/04/2011	26/06/2012	15 months	4
23	701	10/08/2013	6/12/2013	4 months	2
24	255	23/05/2009	12/10/2010	16 months	
25	408	_	_	_	
			Mean time between injury and surgery:	**9.7 months**	
Group 2 (10 to 20 years post-operative)					
27.	789	21/06/1997	19/01/1999	18 months	17

	Participant ID	Accident Date	Date of Surgery	Time between injury and surgery	Time since ACLR (years)
28.	467	_	_	_	12
29.	634	_	_	_	11
30.	206	_	_	_	10
31.	408	_	_	_	17
32.	703	_	_	_	13
33.	797	_	_	_	12
34.	491	_	_	_	12
35.	851	_	_	_	13

Time since ACLR and number of participants in that range (Group 1): 2 years post-op: 1 participant, 3 years post-op: 4 participants, 4 years post-op: 6 participants, 5 years post-op: 7 participants, 6 years post-op: 1 participant, 7 years post-op: 1 participant, 8 years post-op: 1 participant, 9 years post-op:2 participants.

Time since ACLR and number of participants in that range (Group 2): 10 years post-op: 1 participant, 11 years post-op: 1 participant, 12 years post-op: 3 participants, 13 years post-op: 2, 17 years post-op: 2 participants.

Appendix D1- Bracket

Rupture of anterior cruciate ligament (ACL) is one of the common injuries in sports. The rupture of ACL commonly occurs in netball, skiing and other non-contact sports. Females are at higher risk of injury because of anatomical and hormonal variations than males. Treatment options include non-surgical treatment where participants go through a rehabilitation protocol with the aim of restoring limb stability and function to pre-injury level. The other treatment option is the reconstruction of the injured ligament with autograft and allograft which is followed by rehabilitation protocol.

Outcomes after ACL reconstruction (ACLR) may vary among individuals and is affected by factor such as the pre-injury level of sports, severity of injury, time between injury and surgery, surgical technique, type of graft, psychosocial factors, self-efficacy of the participant and type of rehabilitation protocol.

Incomplete recovery of thigh muscle strength and persistence of pain is reported by some of the patients following surgery. Factors responsible for persistence of muscle weakness are still being explored, and factors such as neuro-physiological mechanisms are reported for pain and quadriceps or hamstring muscle atrophy. The treatment options to deal with the residual atrophy and pain successfully are still fewer and this can be challenging for patients to deal with. Muscle weakness may also be related to the graft site morbidity. Patients with patellar tendon graft present with quadriceps weakness and pain during kneeling activities whereas those with hamstring graft present with hamstring muscle weakness. Pain and major thigh muscle weakness can influence the social and health-related quality of life. Pain can lead to modifying or reducing level of activities. Problems related to returning to pre-injury level of work are reported more during the initial 2-3 years after surgery and after that most of the individuals are able to develop their own adapting strategies. Physiotherapists and surgeons should aim to restore the participant to pre-injury level of activities.

Inability to achieve the pre-injury level of activities and confidence in the knee is the biggest regret by majority of the participant following ACLR. Only 45% of the operated individuals are able to return back pre-injury level of sports and activities. Fear of re-injury on the operated side makes the participants to be selective for less risky and safe options when it comes to going full out at sport. A sports psychologist should be the part of the rehabilitation team and should try to restore the patient’s confidence in their knee to eradicate the fear of injury. Some of the experienced and national level soccer players also express their concern about their inability to go ‘full out’ as they used to before injury. Fear of re-injury and constant awareness about the operated knee hinders the performance of the players.

Patients with ACLR can have some further consequences after surgery, one of them being at risk of post-traumatic osteoarthritis years after reconstruction. Different underlying mechanisms are believed to be responsible for this: for example, partial recovery of muscle strength or the abnormal loading of the cartilage. Usually patients are aware of these consequences and are also motivated to stick to the exercise regimen. Another consequence to ACLR is the risk of re-injury to the ipsilateral and contralateral knee joint. Anatomical variations, ligament laxity and abnormal kinematics and kinetics can make a participant prone to re-injury.

To summarize, overall, patients seem satisfied with their knee surgery although it has influenced their family, social and professional life to a large extent. Patients are continuously concerned about their knee during daily activities and have poor confidence in the knee along with fear of re-injury. Hence, ACLR influences activity levels, health–related quality of life and social life of the participant to differing extents.

Appendix D2- Additional participant quotes

Themes	Subtheme	Categories	Quotes
1. Fear of re-injury versus confidence continuum	Causes of fear of injury	Fear of experiencing injury pain associated with the initial injury again	"I've got no control whatsoever ice skating and I just feel like I would be at too much of a risk of doing something to myself. I was a good enough skier beforehand that I've got the control to do it whereas I've got no control whatsoever ice skating and I just feel like I would be at too much of a risk of doing something to myself and it's that knowing that yes, it is a possibility to do again whether it would be the same knee or the other knee and, but I don't want to do it again." P1
			"I don't like running, I don't like high impact sports, too scared to go back to skiing because I know several people who had the operation and they re-injured their knee, when they had a crash, so I am quite happy the way my knee is there, I don't want to re-injure it, I keep away from contact sports and skiing which is a shame but I am happy the way it is. It's partly is the fear that I will re-injure my knee. I am just worried that I will fall of my knee, that's all…you know." P3
			"I just would never want to go through it again, I mean I know I could get through it but it's, yeah it buggered me up for a bit…." P6
		Memory of inciting injury movement	"…it kind of scares you 'cause you know exactly how you've done it and how you could do it again so like just trying to avoid doing a similar movement to what I did at the time I guess." P4
		Long rehabilitation period and loss of muscle strength	"So it's definitely less weight on the leg with the reconstruction when it comes to anything using my quads." P1

Themes	Subtheme	Categories	Quotes
		Impact of the injury and rehabilitation on family responsibility	"…I don't do stuff with the kids which I would, like I'd probably run around and kick a ball around outside with them." P2
	Behavioral manifestations of fear of re-injury	Concern about playing conditions	"Yeah [playground conditions] that sort of plays a role, definitely when it is muddy surface and wet surface, which we quite often get in Dunedin…., Yeah you do think about it." 'P5
			Slippery surfaces is one that I am concerned about in the Winter especially, icy stuff….." P9
			"Yeah wet muddy surface, I don't know I worry about you know, your foot getting lost and it twisting…., yeah so pretty cautious about surface." P5
			"Just the uneven surface makes me feel uncomfortable." P8
			"I wouldn't play football on the hard concrete with the kids." P6
			"I can't do the same weights on that leg but otherwise it doesn't really stop me from doing anything that I want to." P1
			"Cos that's how I did it when I was turning on my foot. 'Cos I wore like studded shoes so just be like when I have to do quick turns playing sport would be one I'd be a bit more cautious and probably like run around it rather than pivoting." P4
			"It's just….. turning. turning, pivoting on my foot is, on that leg is what scares me. I don't know why it doesn't scare me on my left but yeah I'm a bit guarded trying to turn on it because that's how I've done it. Probably just because I do guard my knee a little bit so it's more just a protective sort of means. But I'm still guarded." P4
			I do guard my knee a little bit so it's more just a protective sort of means. P4
			"Yeah it's good. It's fine. I don't worry about that too much. The only direction thing I worry about now is with water skiing. So if I have my left foot forward and my right foot back I'm fine

Themes	Subtheme	Categories	Quotes
			turning, no I’m fine turning left, problems turning right. And again I don’t know if it’s strength or mind.” P9
		Hesitation in sports during certain movements	“Yeah definitely with like lunges, like I’ll do walking lunges but I won’t do the jumping lunges just because I know at all the time. I spent a lot of time in front of the mirror like watching my knee, you know making sure that it was in line and 'cause gym? doesn’t have any mirrors, it’s like I don’t want to…but lunges, I just, yeah I’m just a bit wary of technique, my techniques not very good so, especially if I don’t have a mirror where I can correct it.” P7
			“I think I can give 100%. …, but it is probably not, you know I don’t do it, I have got to think about it a little bit and […] convince myself, no I am fine to go all out here, and I have done that through this last part of the season and have realised that I can handle it and it withstands all that effort.” P5
			“I was pretty reckless then and fearless and now I think about it a bit more and go, ok I might sort of hold out of that tackle; might not lunge for that ball.” P5
			“I was a bit afraid, like for the sort of turning and twisting and kicking stuff because I’m not, soccer’s not one of the sports I’ve played a lot, that I might do something to myself.” P1
			“I make sure …. that every turn I take is done well.” P9
			“Downhill, putting pressure forward, so if I was jumping down a slope I’d be quiet nervous.” P9
			“I think twice if I’m changing my direction very quickly on that, on my right knee.” P10
		Use of brace while playing	“[Strapping] usually if I’m on a mountain that I’m less familiar with.” P1
			I don’t know if it [brace] was doing anything or if it just gave me confidence in my mind but I seemed to have, it doesn’t seem to make a difference to how I actually ski whether I wear it or not but I certainly don’t wear it for any other activities anymore.” P1

Themes	Subtheme	Categories	Quotes
			“Only on the heavier weights [during gym training]. Because on the heavy lifts as you mentioned before sometimes when fatigue kicks in there’s a bit of wobble on your joints.”
	Confidence	The fluctuating confidence spectrum	“I think it is that, it is still that lack of confidence you know.” P5
			“It’s pretty fine. Like I don’t really notice it.” P4
			“Probably a lot more disability is in my head, I can recognize it now and I probably could run, it might need just take pain killers.” P3
			“I’m like an old lady knees aye.” P2
		Positive attitude	“I said I won’t do any less but I won’t do any more so whatever the physio told me to, whatever the rehab people said, I did exactly that and I hit all the marks so when he said when you’re gonna be walking, I was walking and when he said you can start going out in the morning and I still remember that….., , it was a great day to be able to run for a minute and then it was just a sliding scale and then just kept going….. and here I am now, ….” P6
2. Live life normally	Influence on life	Modified life style	“I don’t jump on the trampoline as much, I do it sometimes but I’m really conscious that it feels, in my head, I think it could go wrong very easily […]. I probably walk, like so I used to walk a lot and now I think if I walked to work, for example then how sore am I gonna be for the rest of the day or will my knee be able to cope then walking home, does that make sense 'cause…” P2
			“…no, not really, mmm, I don’t need to do much physically, like the idea of having a standing desk is quite appealing but I wouldn’t, I’m concerned that if I was to do that, I couldn’t handle it, like standing for too much might be worse” P2
			“..yeah and so I don’t do stuff with the kids which I would, like I’d probably run around and kick a ball around outside with them”

Themes	Subtheme	Categories	Quotes
		Change in priorities and attitudes towards physical activity	I'm just mindful of ok this is probably one of those times where you can either button off or you just take it a wee bit easy, you know better to be cautious than to go oh crap…" P6
			"I probably am just a little bit more careful [,…] I never really was into high risk stuff anyway but [……] I've got flatmates that go long boarding and [..] sliding down [the street] on food trays and stuff. I don't know whether I would think differently but my reason was sort of […] I won't do that 'cause my knee's not better so I don't know whether I use it as an excuse to not do something I already don't wanna do, or whether if I felt really strong and more invincible than I do feel, maybe I would, I dunno but it's probably a good thing…..." P7
			"…..With my kids if, you know 'cause that's another thing, they're a bit bigger now but until quite recently, I was holding my little one a lot and ….., now I have to say to them just don't climb on me, don't, because it's just too, too hard...." P2
3. Need of reassurance and maintenance of knee health	Seeking health professional's advice	Continuing daily struggles	"Yeah, yeah, so like sitting, if I, I have to sit on the ground quite a bit, like with the kids or with my work sometimes we do and getting up's sore, like sitting down." P2
			"I can't kneel for example or just, if I even have to kneel down to get something, it hurts and sometimes if I kneel on something, where the scar is, it's shocking so yeah, and driving after a while, it gets sore." P2
			"…it's not that I don't actually like doing it and once I do it, the trouble I have is getting down 'cause generally, like I'm usually someone who moves really fast and from position to position but I can't, I have to get myself in one place that I can then reach everything." P2
			"Yes, I have got with daily activities,…if I run it hurts, if I rise upstairs it clicks a lot then." P3.

Themes	Subtheme	Categories	Quotes
			Yeah …. like sitting, if I, I have to sit on the ground quite a bit, like with the kids or with my work sometimes we do and getting up's sore, like sitting down, …..I can't kneel for example or just, if I even have to kneel down to get something, it hurts and sometimes if I kneel on something, where the scar is, it's shocking …., and driving after a while, it gets sore…" P9
			"Yeah I don't like to, well I do run on concrete a bit but I really prefer not to, just 'cause like I get a lot more pain, yeah a little bit more pain, not a lot but definitely the softer surfaces, so it's just a little bit tender for like that real hard impact kind of stuff." P7.
			"Because I think that is where I would lock my knee out and then that is the kind of feeling I don't like, so sprinting is hard and it is quite scary. I guess that is how I perceive going hard out and going full on, in sport is being able to sprint and that is the one thing that I haven't been able to do. Changing direction is fine, I am able to change direction, I am able to jump, it is just the sprinting." P8
			"It [Pain] would be less than that probably. It would be behind my kneecap. It would be more after sport than during. So like if I've worked pretty particularly hard on that leg. …It might get a bit sore but even then I'd say it's less than every month. It'd be like every three or four months and it wouldn't last more than a day." P8
			"Yeah but it's this, it's like a flow on effect aye, I've had the most trouble with my hip which we think is resultant from the knee, …you know how your body compensates, …and I've had it looked at by physios and osteos and all that kind of stuff and it's linked to the knee." P9 "….it still give me pain and it wasn't sore when I had the operation done." P9
			" I'm just worried about when I get old, it's gonna be really sore but immediate future, no issues." P7

Themes	Subtheme	Categories	Quotes
			"Yea, I expect to have knee replacement in future at some point, may be hip replacement too." P3
			"I do take two Panadol two ibuprofen in the morning because if I don't by the end of day it hurts.., yep every day, and I find if I forget to take those pills in the morning by it hurts bit, if I take it is fine, and you sort 18 hours of the day, 10 hours of the day pain free, and the days if no pills during the day, when I have forgotten them by lunch time." P3
			"Cause I know that when I say problem its I know for a fact, I know that this is not as good as my left and I still have this fear in my head that my knee is going into valgus . That's my biggest fear currently. I had to do two hundred kg squat or whatever, I had to reach failure by eight and I reached it by eight with that weight so, and I thought it was appropriate weight. But because its heavy I sometimes I feel my knee wobble a little bit and going, I don't know maybe it didn't go out but I thought it was going valgus which I did notice my left leg was completely stable." P10
			"Sometimes if it, you know, if it pops really hard there's a bit of discomfort but nothing, major." P10
			"I can't do the same weights on that leg but otherwise it doesn't really stop me from doing anything that I want to. So it's definitely less weight on the leg with the reconstruction when it comes to anything using my quads." P1
			"Not enough that I avoid stairs, it's just that, it only happened last year that one day I was going up some stairs and there was a big click and it hurt briefly and then since then I've noticed it make more noise as I go up and down stairs and it's just, it's not even pain, it's just there's a little bit of discomfort." P1
			"I can't kneel on a hard surface for very long at all, I usually transfer all the weight over to the other knee straight away, if there's a cushion or something soft, then yes but not like on the floor." P1

Themes	Subtheme	Categories	Quotes
			"My knee like locked at the start so I just had to think about ok, I just need to … change what I'm doing, so …. I can sit on my knee a lot but it doesn't stop me from doing stuff, it's more like I just have to re-think how I'm gonna like do stuff…." P7
			"I don't know maybe I won't like kneel on it for a while, something like that will be about the only thing that affects me in every day." P5
			"Achiness after running, I'm not sure what that's caused to, and achiness when it's really cold in the Winter, in the morning. Now and then down stairs I'm conscious of it. I don't jump around and leap from things how I used to. I'm definitely cautious with it." P9
			"Yeah …. like sitting, if I, I have to sit on the ground quite a bit, like with the kids or with my work sometimes we do and getting up's sore, like sitting down, …..I can't kneel for example or just, if I even have to kneel down to get something, it hurts and sometimes if I kneel on something, where the scar is, it's shocking …., and driving after a while, it gets sore…" P9
		Patient specific concerns	"…….I could approach them and say, hey I need some exercises because I feel like I am getting quite weak or something like that, but otherwise, no, I don't think. They could probably do a follow up maybe; I guess that could be quite good." P8
			"Yeah,….. just continual care '…you know like when you get switched around to too many people, they just don't, you can't get that continuity and so having that is like the best thing I reckon, yeah." P7
		Graft-site related weakness	"My left leg is considerably stronger than my right which is quite annoying as that is my dominant leg. On a day to day basis it's not very noticeable because the strength of the right leg is more than enough for my activities." P10
			"Yes I did afterwards, but I tried to get, I tried to get um in recovery get back to everything too quickly. I had a bit of a strain in (Hamstring) there" P9

Themes	Subtheme	Categories	Quotes
			"…yet the main [Hamstring] injuries I got were training for the marathon because it was repetitive" P6
		Maintenance of the muscle strength	"Yeah I think probably my fear of injury is less when I'm stronger so I just remember like when I was going through my rehab, I was ….was supposed to jump onto this box, it was …..this high, not even 30cm…and you had to jump and that scared me so much but like as I got stronger, I was like yep, no this is alright, like I can, so like the stronger I get, the less worried I am about injury and then I get weak again, I'm like oh it could go but I know that's not true 'cause it's a ligament and you know like, but it's just the feeling of being strong and yeah and knowing that you've got a lot of support around my knee, just yeah that would make me a lot more confident, yeah" P7.
	Concern for long term disabilities	Concern for osteoarthritis and knee replacement	"I guess I do have the vague wondering if I'm going to end up with osteoarthritis or not in the knee." P1
			"Ah well maybe if I stop being so mobile, will it stiffen up more, I don't know, I mean not." P6
			"My concerns is that people say that if you have ACL surgery you're likely to need a knee replacement in the future."P9

Appendix D3- Data check with the participants for qualitative study

Patients' perspectives of the outcomes of anterior cruciate ligament (ACL) reconstruction of the knee.

"Living with the ACL-reconstructed knee."

Mandeep Kaur, Ph.D. Student
Dr Daniel Ribeiro, Senior Lecturer
Prof. Jean-Claude Theis, Dunedin Hospital
Assoc Prof Kate Webster, La Trobe University, Australia
Dr Gisela Sole, Senior Lecturer

Centre for Health, Activity and Rehabilitation Research
School of Physiotherapy
University of Otago

We thank you for participating in this research study and for the information that you shared with us. We hereby would like to provide you with a summary of the results and invite you to respond to us if there is any further aspect you would like to highlight, or if you feel the summary below does not portray your experiences.

Why this study was conducted.

We were interested to explore the experiences of individuals who had undergone an anterior cruciate ligament (ACL) reconstruction within the past 2 to 10 years. We focussed on the impact of the injury and surgery on the individual's lives and overall quality of life, from your perspective. A further aim of this study was to explore if individuals who had undergone such surgery have any concerns related to the knee which we, as health care professionals, should be considering during usual clinical consultations. This information would allow us to understand the patients' perspectives and provide more individualised approaches to rehabilitation and management of long-term knee health.

Results of the study

We interviewed ten volunteers and the recording of the interviews were transcribed. The researchers then analysed the transcriptions, and defined main themes and sub-themes that emanated from them.

The following main themes were defined after analysis of the interview data and discussions within the research team: The fear of re-injury and confidence spectrum; Maintenance of knee health; Need of reassurance; and Live life normally.

1. The fear of injury and confidence spectrum:

Engagement with physical and sports activities appeared to be influenced by a spectrum or continuum between fear of re-injury and confidence, irrespective of the time since surgery. A wide confidence spectrum was seen among the participants where three participants described themselves as confident, one was in the process of gaining confidence, and two described their confidence levels as being low with regards to their sports performance. Those with less fear of reinjury appeared to be playing at higher levels of sports and had minimal hesitation while playing. Fear of injury seems to be driven by the participant's experiences with ACL injury and surgery, often sub-consciously avoiding movements that caused the initial injury. However, the fear (and confidence) appeared to be fluctuating depending on the physical task. Self-esteem, perseverance, and following the instructions given by the health professionals during rehabilitation prior to and following surgery were reported as the key to success after surgery.

2. Need of reassurance and maintenance of knee health:

Most participants discussed the importance of seeking on-going advice from the health care professionals regarding the specific needs related to their knee health. Those who had been able to return to sports reported having issues, such as graft site-related weakness, and hesitancy during certain movements in sports while less active participants appeared to have minor daily struggles, such as pain during kneeling or pain after sitting for long stretches of time. Most of the participants had some concerns about getting knee osteoarthritis in future. They appeared to consider a long term maintenance programme, particularly for the thigh muscles, important to maintain and improve self-confidence.

3. Live life normally:

The participants' overall approach was to continue with life as normally as possible in terms of activities of daily life, professional life and other social domains, although they had modified life style strategies, priorities and attitude towards physical activity. While most of the participants were cautious and mindful towards their knee during physical activity, participants with unsatisfactory outcomes appeared to be more anxious about their knee and described avoiding physical activities that loaded their knee. A spectrum of recovery was apparent among the participants varying from interfering effect on their life to minimal effect of their injury to their present lives.

The results of this study adds towards health care professionals' understand of the patients' specific needs and sports-related concerns following ACL injury and surgery. The results show that, overall, participants were motivated to live their life normally and had minimal pain and knee-related symptoms. However, they continued to experience sporadic fear of re-injury and low confidence levels during very specific sporting or physical activities. Maintaining the thigh muscle strength were seen as a self-strategy to maintain confidence and knee health, and graft-site related weakness and the possibility of future symptoms were some of the patients' concerns.

The results of the study will be published in the thesis written by Mandeep Kaur for her Ph.D. degree. We will also be submitting a manuscript for publication in an international journal.

Please respond to Mandeep Kaur at mandeep.kaur@otago.ac.nz before 1st March, 2017.

Thank you once again for helping us with this research.

Yours Sincerely,
Mandeep Kaur

Appendix E1- Visual 3D algorithm for determining gait events

<u>In trials</u>:

- Odd no. - going upstairs
- Even no.- downstairs

<u>Axis and movements</u>

- X axis- flexion
- Y axis- medial-lateral movement
- Z axis- rotation

<u>Pipelines:</u>

- 1 Model; Loading of trials, analyzing gait phases
- 2 Model: Moments
- 3 Model: Getting all the data and saving it.

<u>Sequence: Pipeline 12 model</u>

1. Open the required folder with C3D files; it should have different files for barefoot and shoe conditions.
2. Open visual 3D.
3. Go to pipeline and click "open".
4. Open the folder to be processed; it should have one static and two dynamic files.
5. Open model (12model).
6. Execute pipeline.
7. Confirm folder (ok).
8. Enter weight/height of the participant
9. Select all by selecting top one, press "Shift" while selecting the lowermost one.
10. Zero errors = acceptable
11. Go to workspace; check individual trials and "ticks" if they are representing the desired trial.
12. Go to Signals and events
13. Open target folder
14. Go to filtered
15. Click on right trial
16. Right click (for left foot)
17. Graph (Z)
18. Right foot
19. Open events label
20. Go to original and highlight the phases for example; LHS, LTo, LToff; for right foot RHS, RTO, RTOFF
21. Go through each trial and make sure two toe off are there and are at right place.
22. Run the trail and see if it is at right place
23. If not; Open E' and chose right frame if not basically right
24. Got through all trials
25. Once checked all, open pipeline and replace

<u>Sequence: Pipeline 22model</u>

1. Execute pipeline
2. Confirm folder
3. Zero errors i.e. acceptable
4. Un-highlight previous selections
5. Highlight moments
6. Right click on graphs and remove all previous graphs
7. Go to link model- based folder

8. Open processed> knee moments
9. Graph X, Y & Z > new graph
10. Go through all graphs
11. “Remove graphs” when to do for other limb
12. Again get new graphs from link-model based> X-Y-Z- new graph
13. If all good > open pipeline> Replace

<u>Sequence: Pipeline 32 matrices model</u>

1. Click open > it will crash if everything is not eight. It has to have 2 toe-offs for each trial
2. If it worked it would create ‘metric folder’.

Note: CMO files will be there, which can be used if we left the processing in between, than go to visual 3D, open COM file and resume the working from where you left.

Appendix E2- MATLAB code to plot the linear envelops for angles and moments

Step 1

```
%% This script reads in, labels and reorganises data exported from Visual3D
%   Written by Peter Lamb
%   27/06/2017

%% Define paths and directories
% Clear the command line and workspace and close all figures
clc; clear variables; close all;

% Identify file directories Enter directory path here, similar to:
root = '/Users/peterlamb/Documents/People/Mandeep Kaur';
dataPath = [root '/data/Mat/'];


%% Set up metadata
% How many .mat files are there in the data path? Should correspond to
% number of participants
matFiles = dir([dataPath '*.mat']);
nParticipants = length(matFiles);

% Identify group: for ACL which leg is injured; for control which leg is
% "side 1".
load([root '/m-files/participant_information_ht_wt.mat'])

% Pre-allocate memory for dataset:
% 1-3 stepping knee angle XYZ, 4-6 stepping knee moment XYZ
nVariables  = 6;
% if ACL, 1=injured, 2=non-injured, if control, 1=left, 2=right.
nLegs       = 2;
max_nTrials = 10;
nDirections = 2;
max_nFrames = 2000;
stairD      = nan(nParticipants, nLegs, nDirections, nVariables, ...
    max_nTrials, max_nFrames);

%% Reorganise data
% Loop through each participant's .mat file and organise into the array.
parInfo = zeros(1000,4);
parCnt = 1;
samp_rate = nan(nParticipants,1);
fp_samp_rate = 1050;
for iPar = 1 : nParticipants

    % Pick the file name of the ith file
```

```
fName = matFiles(iPar).name;

% Load the ith file
load([dataPath fName])

% Determine frame rate and save
samp_rate(iPar) = FRAME_RATE {1,1}(1,1);

% Fix variable naming inconsistencies
if exist('kneeMomentsR', 'var')
    KneeMomentsR = kneeMomentsR;
    clear kneeMomentsR
end

% Create Participant ID variable
id = str2double(fName(1:end-4));

% Find row index to ith participant ID in labels
labelRow = find([labels {:,1}] == id);

% Record missing participants and jump to next if found
if isempty(labelRow)
    parInfo(parCnt,:) = [iPar id NaN 999];
    parCnt = parCnt + 1;
    continue
end

% Create Participant 'group' variable
group = labels{labelRow, 2};

if strcmp(group, 'Control')
    group = 0;
else
    group = 1;
end

weight = labels{labelRow, 4};

height = labels{labelRow, 5};

% Create participant leg variable, group=ACL leg represents injured
% leg, if group=control, leg represents side 1 leg.
parLeg = labels{labelRow, 3};

% Find the number of trials so that we can loop through the trials
nTrials = length(FILE_NAME);

% Start counters
```

```
ascCounterL = 1; ascCounterR = 1;
dscCounterL = 1; dscCounterR = 1;

for iTrial = 1 : nTrials

    % Read trial number and leg from FILE_NAME (MATLAB orders numbers
    % differently e.g. 1, 10, 2, 3, ...)
    scanned     = textscan(FILE_NAME{iTrial,1}, '%s', 'delimiter', '\');
    lastpart    = textscan(scanned{1,1}{end,1}, '%s', 'delimiter', '_');
    trialLeg    = lastpart{1,1}{2,1}(1);
    trialNum    = str2double(lastpart{1,1}{2,1}(2:end-4));

    % Check that required data are available
    if (strcmp(trialLeg, 'L') && (isempty(KneeAngL{iTrial,1}) || ...
            isempty(KneeMomentsL{iTrial,1}))) || ...
            (strcmp(trialLeg, 'L') && (isempty(KneeAngR{iTrial,1}) || ...
            isempty(KneeMomentsR{iTrial,1})))
        parInfo(parCnt, :) = [iPar id group trialNum];
        parCnt = parCnt + 1;
        continue
    end

    % Determine number of frames
    nFrames = length(KneeAngL{iTrial,1});

    % Determine which leg, 1 if stepping leg is injured (or side 1), 2
    % if not
    if (strcmp(parLeg, 'l') && strcmp(trialLeg, 'L')) || ...
            (strcmp(parLeg, 'r') && strcmp(trialLeg, 'R'))
        legInd = 1;
    else
        legInd = 2;
    end

    % Determine ascending or descending
    if mod(trialNum,2)==0
        directionInd = 2;
    else
        directionInd = 1;
    end

    % Identify start and end points using force data
    fData       = FP2{iTrial,1}(:,1);
    fpFrames    = length(fData);
    old_time    = (0:fpFrames-1)/(fpFrames-1);
    new_time    = (0:nFrames-1)/(nFrames-1);
    fDresamp    = interp1(old_time, fData, new_time, 'pchip');
    nonzero     = find(fDresamp);
```

```
first      = nonzero(1);
last       = nonzero(length(nonzero));
new_len    = 1:(last-first)+1;
% Downsample to common frame rate with mocap

% If ascending, use the ascending trial counter - ascCounter
if directionInd==1

  % If the left leg is being, start with left knee variables and
  % transform Y and Z
  if strcmp(trialLeg, 'L')
    stairD(iPar, legInd, directionInd, 1, ascCounterL, new_len)...
      = KneeAngL{iTrial,1}(first:last,1);
    stairD(iPar, legInd, directionInd, 2, ascCounterL, new_len)...
      = KneeAngL{iTrial,1}(first:last,2)*-1;
    stairD(iPar, legInd, directionInd, 3, ascCounterL, new_len)...
      = KneeAngL{iTrial,1}(first:last,3)*-1;
    stairD(iPar, legInd, directionInd, 4, ascCounterL, new_len)...
      = KneeMomentsL{iTrial,1}(first:last,1)/height/weight;
    stairD(iPar, legInd, directionInd, 5, ascCounterL, new_len)...
      = KneeMomentsL{iTrial,1}(first:last,2)*-1/height/weight;
    stairD(iPar, legInd, directionInd, 6, ascCounterL, new_len)...
      = KneeMomentsL{iTrial,1}(first:last,3)*-1/height/weight;

    % Else if the right leg is being used, start with the right
    % knee variables
  else
    stairD(iPar, legInd, directionInd, 1, ascCounterR, new_len)...
      = KneeAngR{iTrial,1}(first:last,1);
    stairD(iPar, legInd, directionInd, 2, ascCounterR, new_len)...
      = KneeAngR{iTrial,1}(first:last,2);
    stairD(iPar, legInd, directionInd, 3, ascCounterR, new_len)...
      = KneeAngR{iTrial,1}(first:last,3);
    stairD(iPar, legInd, directionInd, 4, ascCounterR, new_len)...
      = KneeMomentsR{iTrial,1}(first:last,1)/height/weight;
    stairD(iPar, legInd, directionInd, 5, ascCounterR, new_len)...
      = KneeMomentsR{iTrial,1}(first:last,2)/height/weight;
    stairD(iPar, legInd, directionInd, 6, ascCounterR, new_len)...
      = KneeMomentsR{iTrial,1}(first:last,3)/height/weight;
  end

  % Else if not ascending, use the descending counter -
  % dscCounter
else
  % If the left leg is being, start with left knee variables and
  % transform Y and Z
  if strcmp(trialLeg, 'L')
    stairD(iPar, legInd, directionInd, 1, dscCounterL, new_len)...
```

```
                = KneeAngL{iTrial,1}(first:last,1);
            stairD(iPar, legInd, directionInd, 2, dscCounterL, new_len)...
                = KneeAngL{iTrial,1}(first:last,2)*-1;
            stairD(iPar, legInd, directionInd, 3, dscCounterL, new_len)...
                = KneeAngL{iTrial,1}(first:last,3)*-1;
            stairD(iPar, legInd, directionInd, 4, dscCounterL, new_len)...
                = KneeMomentsL{iTrial,1}(first:last,1)/height/weight;
            stairD(iPar, legInd, directionInd, 5, dscCounterL, new_len)...
                = KneeMomentsL{iTrial,1}(first:last,2)*-1/height/weight;
            stairD(iPar, legInd, directionInd, 6, dscCounterL, new_len)...
                = KneeMomentsL{iTrial,1}(first:last,3)*-1/height/weight;

            % Else if the right leg is being used, start with the right
            % knee variables
        else
            stairD(iPar, legInd, directionInd, 1, dscCounterR, new_len)...
                = KneeAngR{iTrial,1}(first:last,1);
            stairD(iPar, legInd, directionInd, 2, dscCounterR, new_len)...
                = KneeAngR{iTrial,1}(first:last,2);
            stairD(iPar, legInd, directionInd, 3, dscCounterR, new_len)...
                = KneeAngR{iTrial,1}(first:last,3);
            stairD(iPar, legInd, directionInd, 4, dscCounterR, new_len)...
                = KneeMomentsR{iTrial, 1}(first:last,1)/height/weight;
            stairD(iPar, legInd, directionInd, 5, dscCounterR, new_len)...
                = KneeMomentsR{iTrial, 1}(first:last,2)/height/weight;
            stairD(iPar, legInd, directionInd, 6, dscCounterR, new_len)...
                = KneeMomentsR{iTrial, 1}(first:last,3)/height/weight;
        end
    end


    % Increase appropriate counter
    if directionInd==1 && strcmp(trialLeg, 'L')
        ascCounterL = ascCounterL + 1;
    elseif directionInd==1 && strcmp(trialLeg, 'R')
        ascCounterR = ascCounterR + 1;
    elseif directionInd==2 && strcmp(trialLeg, 'L')
        dscCounterL = dscCounterL + 1;
    else
        dscCounterR = dscCounterR + 1;
    end

  end
  parInfo(parCnt,:) = [iPar id group 0];
  parCnt = parCnt + 1;
end

% Check for unique sampling rate values, if consistent across experiment
```

```
% proceed to save variables to file
samp_rate = unique(samp_rate);
if length(samp_rate) > 1
    error('Inconsistent sampling rates!')
end

% Save variabels to .mat file
save([root '/data/step1_reorganised_trimmed_data.mat'], 'stairD', ...
    'parInfo', 'samp_rate', 'labels', 'id')
```

Step 2

```
%% This script loads reorganised data and processes them
%   Written by Peter Lamb
%   03/07/2017

%% Define paths and directories
% Clear the command line and workspace and close all figures
clc; clear variables; close all;

% Identify file directories
% Identify file directories Enter directory path here, similar to:
root = '/Users/peterlamb/Documents/People/Mandeep Kaur';
dataPath = [root '/data/'];

%% Set up metadata

variableNames = {'Knee angle (X)'; 'Knee angle (Y)'; 'Knee angle (Z)';...
    'Knee moment (X)'; 'Knee moment (Y)'; 'Knee moment (Z)'};
directionNames = {'Asc'; 'Dsc'};

% Load data
load([dataPath 'step1_reorganised_trimmed_data.mat'])

% Redefine for looping:
% 1-3 stepping knee angle XYZ, 4-6 stepping knee moment XYZ
nVariables  = 6;
% 1=ACL, 2=control
nGroups     = 2;
% if ACL, 1=injured, 2=non-injured, if control, 1=left, 2=right.
nLegs       = 2;
max_nTrials = 10;
nDirections = 2;
max_nFrames = 2000;
% stairD dimensions: 1-participant, 2-experimental group, 3-experimental
% leg, 4-step direction, 5-variable, 6-trial, 7-frame
nParticipants = size(stairD,1);
```

```
% Set up filter
cutoff = 15; % Mandeep used 15 Hz in Visual3D
% Number of passes = 2 since using filtfilt:
% http://biomch-l.isbweb.org/archive/index.php/t-26625.html
N = 2;
% Butterworth best for kinematics
% http://dx.doi.org/10.1016/S1050-6411(03)00080-4
f = (sqrt(2)-1)^(1/(2*N));
normCutoff = (2*cutoff)/samp_rate/f;
 % 'double 2nd order Butterworth filter' (Winter, 2009)
[b, a] = butter(N, normCutoff, 'low');

% Declare number of frames for normalisation
nFrames = 101;

% Preallocate output variable
processed = nan(nParticipants, nLegs, nDirections, 5, nVariables, nFrames);

%% Temporary testing and error variables
% Record missed trials and set up counter
errorLog = zeros(100, 5); errorCnt = 1;
% Record trim frames
trimLog = nan(1000,2); trimCnt = 1;

%%
% Loop through participants
for iPar = 1 : nParticipants

    % Loop through experimental leg use
    for iLeg = 1 : nLegs

        % Loop through stepping direction
        for iDir = 1 : nDirections
            dCells = ~isnan(squeeze(stairD(iPar, iLeg, iDir, :, :, :)));
            dCols = find(sum(squeeze(dCells(1,:,:)),2));

            % Loop through variables
            for iVar = 1 : 6

                % Just to be safe check if there are more than 5 trials
                if numel(dCols) > 5
                    error('Unexpected number of trials!')
                end

                % Loop through trials
                for iTrial = dCols'
```

```
                % Create temporary variable
                D = squeeze(stairD(iPar, iLeg, iDir, iVar, iTrial, :));

                % Remove NaNs
                dRows = ~isnan(D);
                D = D(dRows,:);

                % Filter data
                filtered = filtfilt(b, a, D);

                % Time normalise
                newTime = (0:nFrames-1)/(nFrames-1);
                oldTime = (0:length(filtered)-1)/(length(filtered)-1);
                normalised = interp1(oldTime, filtered, newTime, 'pchip')';

                % Assign to output variable
                processed(iPar, iLeg, iDir, iTrial, iVar, :) = normalised;
            end
        end
    end
  end
end

% Save variables to .mat file
save([dataPath 'step2_processed_data.mat'], 'processed', 'parInfo', 'labels')
```

Step 3

```
%% Load processed data and create plots
%  Written by Peter Lamb
%  04/07/2017

%% Define paths and directories
% Clear the command line and workspace and close all figures
clc; clear variables; close all;

% Identify file directories Identify file directories Enter directory path
% here, similar to:
root = '/Users/peterlamb/Documents/People/Mandeep Kaur';
dataPath = [root '/data/'];

% Load data
load([root '/data/step2_processed_data.mat'])
% KEY: 'processed' dimensions: 1-participant, 2-experimental leg, 3-step
% direction, 4-trial, 5-variable, 6-frame

%% Set up common plot parameters
```

```
variableNames = {'Knee angle (X)', 'Knee angle (Y)', 'Knee angle (Z)',...
   'Knee moment (X)', 'Knee moment (Y)', 'Knee moment (Z)'};
direction   = {'Ascending', 'Descending'};
units       = {'Degrees', 'Degrees', 'Degrees', 'Nm / (ht*wt)', ...
   'Nm / (ht*wt)', 'Nm / (ht*wt)'};
alpha       = .15;

% Axis positioning, x-axis index, number of variables, order to run through
% variables and strings to label file names for export.
x_pos   = repmat([0.09 .57], 3, 1)';
y_pos   = repmat([.73 .41 .1], 2, 1);
x       = (1:101)';
nVars   = 6;
vOrder  = [1 4 2 5 3 6];

%% (1) Create 6 panel with ACL injured, non-injured and Control side 1 plot
% for each stepping direction.

% Determine which participants are ACL and Control (important for reshape
% below)
aclRow      = parInfo(:,3) == 1 & parInfo(:,4) == 0;
contRow     = parInfo(:,3) == 0 & parInfo(:,4) == 0 & parInfo(:,1) > 0;
aclPar      = parInfo(aclRow,1);
contPar     = parInfo(contRow,1);

% Loop through stepping direction
for iDir = 1 : 2

   % Create figure axis handle
   f = figure('units','centimeters','Position', [10 10 19 14]);
   axCnt = 1;

   % Loop through variables in order of vOrder to get angles in first
   % column and moments in second column.
   for i = vOrder

      % Extract data for ACL injured leg
      inj     = reshape(processed(aclPar, 1, iDir, :, i, :), ...
         sum(aclRow)*5, 101)';

      % Mean (ignoring NaN if any)
      mnInj   = nanmean(inj, 2);

      % Standard deviation (ignoring NaN if any)
      sdInj   = nanstd(inj, 1,2);

      % Extract data for ACL non-injured leg
      non     = reshape(processed(aclPar, 2, iDir, :, i, :), ...
```

```
    sum(aclRow)*5, 101)';
  mnNon   = nanmean(non, 2);
  sdNon   = nanstd(non, 1, 2);

  % Extract data for Control side 1
  cont    = reshape(processed(contPar, 1, iDir, :, i, :), ...
    sum(contRow)*5, 101)';
  mnCont  = nanmean(cont, 2);
  sdCont  = nanstd(cont, 1, 2);

  % Set up axis for current panel
  ax(i) = axes('Position', [x_pos(axCnt) y_pos(axCnt) 0.4 0.22]);
  hold on

  % Draw the standard deviation clouds for each condition
  h1 = fill([x; flipud(x)], [mnInj-sdInj; flipud(mnInj+sdInj)], ...
    [.9 0 0], 'linestyle', 'none');
  h2 = fill([x; flipud(x)], [mnNon-sdNon; flipud(mnNon+sdNon)], ...
    [0 0 .9], 'linestyle', 'none');
  h3 = fill([x; flipud(x)], [mnCont-sdCont; flipud(mnCont+sdCont)], ...
    [.9 .9 .9], 'linestyle', 'none');

  % Make SD clouds mostly transparent
  set([h1 h2 h3], 'facealpha', alpha)

  % Plot mean lines
  p1 = plot(mnInj, 'r', 'LineWidth', 1);
  p2 = plot(mnNon, 'b', 'LineWidth', 1);
  p3 = plot(mnCont, 'k', 'LineWidth', 1);
  box on
  % Make axis fit data range
  axis tight

  % Label panel with variable name
  title(variableNames{i})

  % Increase axis counter
  axCnt = axCnt + 1;

  % Axis labels
  ylabel(units{i})

  if i == 3 || i == 6
    xlabel('Normalised Time (%)')
  end
end
if iDir==1
  legendflex([p1 p2 p3], ...
```

```
            {'Injured (ACL)', 'Non-injured (ACL)', 'Control'},...
            'ref',          ax(1),      'xscale',       0.3, ...
            'box',          'off',      'anchor',       {'nw','nw'},...
            'buffer',       [2 0],      'fontsize',     10)
    else
        legendflex([p1 p2 p3], ...
            {'Injured (ACL)', 'Non-injured (ACL)', 'Control'},...
            'ref',          ax(1),      'xscale',       0.3, ...
            'box',          'off',      'anchor',       {'sw','sw'},...
            'buffer',       [2 0],      'fontsize',     10)
    end
    % White background once figure is complete
    set(f, 'color', 'w')

    % Export using export_fig for best quality, opengl renderer needed for
    % transparency
    export_fig(f, [root '/plots/group_plots/' direction{iDir} '.png'],...
        '-png', '-opengl', '-r300')

    % Close figure
    close(f)
end

%% (2) Create 6 panel plots for each participant and each stepping direction.

% Number of participants
nPar    = size(processed, 1);

% Loop through participants
for iPar = 1 : nPar

    % Create group label string to use in title text
    pRow = parInfo(:,1) == iPar & parInfo(:,4) == 0;
    if parInfo(pRow,3) == 1;
        groupStr = 'ACL';
    else
        groupStr = 'Control';
    end

    id = parInfo(pRow,2);

    % P16 missing
    if isempty(id)
        continue
    end

    for iDir = 1 : 2
```

```matlab
        % Create figure axis handle
        f = figure('units','centimeters','Position', [10 10 19 14]);

        % Loop through variables
        axCnt = 1;
        for iVar = vOrder

            mnInj = nanmean(squeeze(processed(iPar, 1, iDir, :, iVar, :)))';
            sdInj = nanstd(squeeze(processed(iPar, 1, iDir, :, iVar, :)))';
            mnNon = nanmean(squeeze(processed(iPar, 2, iDir, :, iVar, :)))';
            sdNon = nanstd(squeeze(processed(iPar, 2, iDir, :, iVar, :)))';
            ax(iVar) = axes('Position', [x_pos(axCnt) y_pos(axCnt) 0.4 0.22]);
            hold on
            h1 = fill([x; flipud(x)], [mnInj-sdInj; flipud(mnInj+sdInj)], ...
                [.9 0 0], 'linestyle', 'none');
            h2 = fill([x; flipud(x)], [mnNon-sdNon; flipud(mnNon+sdNon)], ...
                [0 0 .9], 'linestyle', 'none');
            set([h1 h2], 'facealpha', alpha)
            p1 = plot(mnInj, 'r', 'LineWidth', 1);
            p2 = plot(mnNon, 'b', 'LineWidth', 1);
            axis tight
            title(variableNames{iVar})
            ylabel(units{iVar})
            if iVar == 3 || iVar == 6
                xlabel('Normalised Time (%)')
            end
            box on
            axCnt = axCnt + 1;
        end
        if parInfo(pRow,3) == 1;
            legendflex([p1 p2], {'Injured', 'Non-injured'},...
                'ref',        ax(1),      'xscale',      0.3, ...
                'box',        'off',      'anchor',      {'nw','nw'},...
                'buffer',     [2 0],      'fontsize',    10)
        else
            legendflex([p1 p2], {'Control Side', 'Non-Control Side'},...
                'ref',        ax(1),      'xscale',      0.3, ...
                'box',        'off',      'anchor',      {'nw','nw'},...
                'buffer',     [2 0],      'fontsize',    10)
        end

        set(f, 'color', 'w')
        export_fig(f, [root '/plots/par_plots/P' num2str(id) '_' ...
            direction{iDir} '.png'],'-png', '-opengl', '-r300')
        close(f)
    end
end
```

Appendix- F1 Assumptions of the multilinear regression- stair ascent

Assumption no. and name	Assumption tested by	Stair ascent Knee flexion moments	Stair ascent Knee adduction moments
Assumption 1	Dependent variable should be measured on a continuous scale	Manually checked: moments are measured on continuous scale	Manually checked: moments are measured on continuous scale
Assumption 2	Two or more independent variables which can be continuous or categorical	Continuous: Quadriceps strength Categorical: Sex	Continuous: Quadriceps strength Categorical: Sex
Assumption 3: Independence of observations	Durbin-Watson statistic	2.502	1.344
Assumption 6: Multicollinearity	Tolerance/VIF values for: 1. Concentric quadriceps strength 2. Time since reconstruction 3. Sex	1.765 1.105 1.852	1.765 1.105 1.852
Assumption 8: Normally distributed residuals	Histograms with superimposed curves	Figure 1	Figure 2

Assumption 8

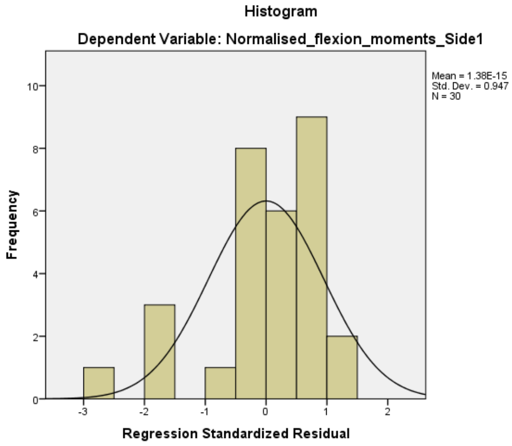


Figure 1. Normally distributed residuals knee flexion moment

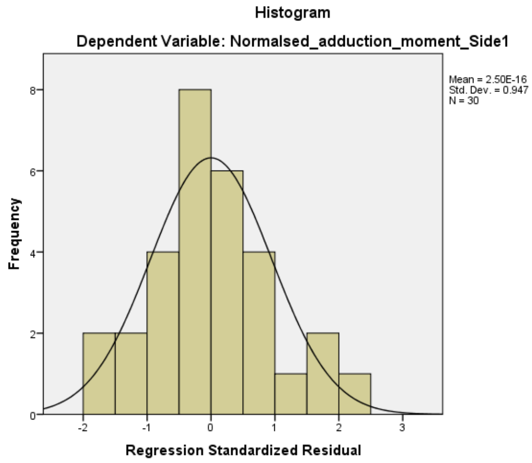


Figure 2. Normally distributed residuals knee adduction moment

Appendix- F2 Assumptions of the multilinear regression- stair descent

Assumption no. and name	Assumption tested by	Stair descent Knee flexion moments	Stair descent Knee adduction moments
Assumption 1	Dependent variable should be measured on a continuous scale	Manually checked: moments are measured on continuous scale	Manually checked: moments are measured on continuous scale
Assumption 2	Two or more independent variables which can be continuous or categorical	Continuous: Quadriceps strength Categorical: Sex	Continuous: Quadriceps strength Categorical: Sex
Assumption 3: Independence of observations	Durbin-Watson statistic	1.609	1.655
Assumption 6: Multicollinearity	Tolerance/VIF values for: 1. Eccentric quadriceps strength 2. Time since reconstruction 3. Sex	 1.384 1.041 1.426	 1.426 1.041 1.426
Assumption 8: normally distributed residuals	Histograms with superimposed curves	Figure 1	Figure 2

Assumption 8

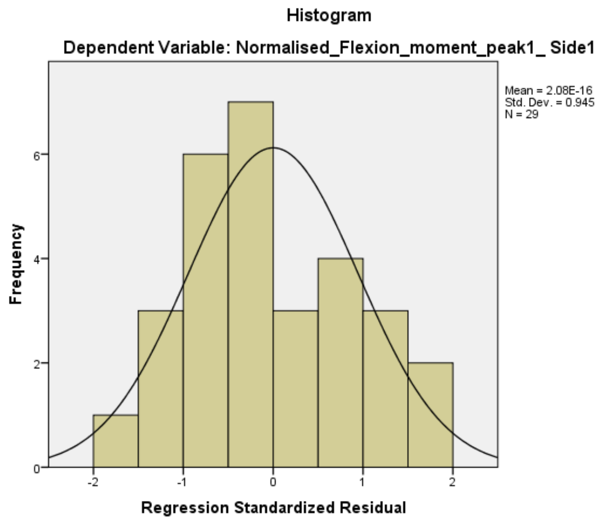


Figure 1. Normally distributed residuals knee flexion moment

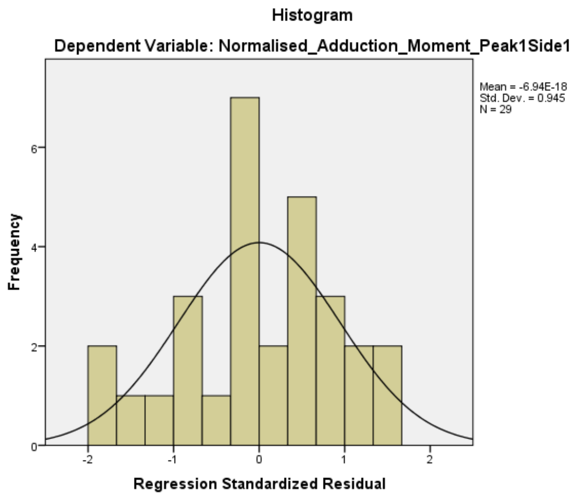


Figure 2. Normally distributed residuals knee adduction moment